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SINGLE CHANNEL SEISMIC EVENT DETECTION

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Several types of seismic signal detectors have been tested on NORSAR and Pinedale, Wyoming signals buried every ten minutes in approximately 22 hours of phase-scrambled noise. All plausible detectors including human analysts operate within 0.1 m_b of the mean value including the present on-line "IBM" STA/LTA detector, a "Z" detector, detectors with fixed or optimum filters, a "deflection" detector, the MARS detector, a detector which cascades a recursive digital filter with Walsh transforms, and human analysts viewing unfiltered Calcomp plots. The best detector was a log-Z transform aided by a recursively updated optimum S/N^2

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filter. Among the worst were human analysts when operating in the "pick everything" mode, the deflection detector, and a prediction-error type detector. The human analyst could, however, improve to be nearly the best if sufficient care was taken. With a modest amount of care, any detector can be modified to perform well as an element of an operational system and the choice of single channel detector can be made on other grounds than pure detection such as availability or computation speed.

In this report also we outline the features of the existing on-line detector at the SDAC which, in addition to pure detection, also classifies events as spikes, drop-outs, regionals, and teleseisms and calculates a refined start time.

SINGLE CHANNEL SEISMIC EVENT DETECTION

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ABSTRACT

Several types of seismic signal detectors have been tested on NORSAR and Pinedale, Wyoming signals buried every ten minutes in approximately 22 hours of phase-scrambled noise. All plausible detectors including human analysts operate within 0.1 m_b of the mean value including the present on-line "IBM" STA/LTA detector, a "Z" detector, detectors with fixed or optimum filters, a "deflection" detector, the MARS detector, a detector which cascades a recursive digital filter with Walsh transforms, and human analysts viewing unfiltered Calcomp plots. The best detector was a log-Z transform aided by a recursively updated optimum S/N^2 filter. Among the worst were human analysts when operating in the "pick everything" mode, the deflection detector, and a prediction-error type detector. The human analyst could, however, improve to be nearly the best if sufficient care was taken. With a modest amount of care, any detector can be modified to perform well as an element of an operational system and the choice of single channel detector can be made on other grounds than pure detection such as availability or computation speed.

In this report also we outline the features of the existing on-line detector at the SDAC which, in addition to pure detection, also classifies events as spikes, drop-outs, regionals, and teleseisms and calculates a refined start time.

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INTRODUCTION

As discussed in more detail in Appendix I, Freiberger (1963) derived the optimum single-channel prefilter and detection procedure using Neyman-Pearson arguments, and Vanderkulk et al (1965) made use of this theory in the design of the operational detector developed for LASA. Vanderkulk et al evaluated by means of theoretical analyses the degradation which would result from various approximations to the optimum procedure and concluded that the difference would be small. Further research on detection proceeded to questions of array detectors which might be resistant to false alarms due to spikes and locals, Blandford (1970, 1972, 1974), to general questions concerning array and network detection, Wirth et al (1971), Shumway (1971), Ringdal et al (1972), Blandford and Wirth (1973) and Wirth et al (1976); to methods of holding the false alarm rate constant, Lacoss (1972), and to various ad-hoc methods of recognizing spikes and local events, von Seggern (1977).

Despite Freiberger's result a number of workers continued to program and test various "intuitive" detectors, e.g. Allen (1978), Shensa (1977), Savino (1979). This, perhaps, derived from the fact that there has never been a direct comparison on the same data base of the optimum detector to other single channel detectors. To remedy this situation we have, as discussed in Appendices II and III, constructed test data tapes on which various research workers may exercise their detectors and via which different detectors may be compared.

In the rest of this study we first outline the capabilities of the computer program which we have written to test various broad-band detectors, and then compare the results (on application to the test tape) of STA/LTA detectors with various averaging times, rectification or squaring, band-pass, Weiner, auto-regressive or prediction-error, and optimum filters, and Z-transformation with or without the log-normal assumption (Shensa, 1977). The conclusion from all this is that the standard band-pass filter with rectification is within 0.1 magnitude unit in performance of the optimum process. We also discuss the performance of the analyst on the data when presented with the data in standard unfiltered develocorder format and compare with results of other contractors' work on these tapes.

OUTLINE OF COMPUTER PROGRAM CAPABILITIES

The basic mode of operation of the 360/44 research program NDP is that of a conventional STA/LTA detector. The data may be read in either from a subset tape (INVSC=0) or from the VSC detector tapes discussed in Appendices II and III, (INVSC=1). If the data are from subset then other parameters specifying the seismogram number, channel and the noise and signal windows are needed, but we shall not consider this case further in this study. When the data are read in they may then either be decimated (I20=1) or not (I20=0); in this study the Pinedale data is decimated and the NORSAR data, originally at 10 sps, is not. The sampling rate of the resulting data is specified, in this study it is always 10 (SR=10). After filtering, which we will discuss later, the filtered data stream is passed to the main detection subroutine (STA/LTA). The filtered data are either squared (IASQ=1) or the absolute value is taken (IASQ=0) and the result is averaged into "YJ" values over non-overlapping windows of SA points. A sliding average of RP of these values is computed and constitutes the STA. For a 10 second STA the parameters used are SA=33 and RP=3 (thus, actually a 9.9 second STA). For all runs in this study, RP=3, and SA is adjusted to give the appropriate time window. The LTA is recursively updated every KR times an STA is computed, and in this study, KR=3, so that the LTA is updated every time a fresh STA is available; therefore, at time intervals which increase as the STA window length increases. This ensures that the LTA will be more stable than the STA. The LTA is updated with a recursive filter according to the formula

$$LTA = 2^{SIG} * STA + (1 - 2^{SIG})\ LTA$$

and in all runs in this paper, SIG=-5. After detection the LTA is updated more rapidly with SIGT replacing SIG and SIGT=-4 so that the event will "turn off" more rapidly to ensure that later phases may be detected. The fact that SIG=-5 and RP=KR=3 implies that the LTA averages over a window about 16-32 times longer than the STA for all runs in this study.

The threshold for detection is V which may be calculated internally in the program or set *a priori* . If it is set *a priori* then it is input as VI; and the turn-off threshold is UI. If it is determined and updated internally then it is calculated from the desired false alarm rate which is specified as the signal window, T divided by the desired time between false alarms TI, both expressed in seconds. The actual modes of threshold calculation are discussed below.

If STA/LTA > V for QT out of QP successive tests then a detection is declared. The on-line SDAC system uses, for reasons of historical continuity, QT=3 and QP=3, and when we are trying to exactly duplicate that detector or small modifications of it, these parameters are used. In general, however, in this paper we use QT=1, QP=3, which simply amounts to detection if STA/LTA exceeds V even once.

Various options exist for filtering of the raw data. There is provision for recursive filtering and several sets of coefficients for bandpass filters exist in the program in data statements. Those used in this study are all for 10 sample per second data and are 6-pole (IRP=6) Butterworth filters for 1.5-4 Hz (suitable for NORSAR) and 1-1.5 and 1-2 Hz (suitable for Pinedale). Recursive filtering is carried out by subroutine RFIL if IOPTF=0. The optimum filter is applied if IOPTF=1. If ISNEQ=0 the signal is assumed to be small and the optimum filter is S/N^2, (see Appendix I). If ISNEQ=1, then S is adjusted in amplitude so that $S/N \leq 1$ but is just equal to 1.0 at some frequency. This signal level should be just detectable and is therefore the signal level for which we optimize the detector. Then, this S is used to compute the optimum filter $S/[N(S^2 + N^2)^{1/2}]$. Unless otherwise noted, this is the filter used in this study. To compute Weiner filters $S^2/(S^2 + N^2)$, a special but simple change to the code is made and again S is adjusted so that $S/N \leq 1$.

The signal amplitude spectrum S is computed as the product of a flat source spectrum times the instrument response (The instrument response is designated in a data statement and is recovered from the RSPCOM disc file.) times the function $\exp(\frac{-\omega t^*}{2})$ where t^* is set to be 0.3 unless otherwise noted in this paper. A flat source spectrum for P waves from small events would be deduced from almost all source theories and observations in the literature although for purposes of this experiment, in which signals from larger events were buried in noise, a corner frequency in the range 1-4 Hz might have been preferable. In any event, we have adopted the flat spectrum as the simplest possibility, and the one which would be correct in application. Obviously, higher values of t^* would be desirable for events from rift zones and other low-Q source regions, and lower values would be suitable for events from shield regions to NORSAR. We shall see, however, that the performance is not overly sensitive to this parameter.

The noise spectrum, N, can, of course, be determined directly from the trace under consideration. There is, naturally, no need to know the system response to calculate the noise spectrum since the noise spectrum as we see it has passed through the system response already. The noise spectrum is obtained from the first IP points (IP=512) of the 10-minute noise plus signal window, and is smoothed with a running averaging window ISMU points long (ISMU=9). If ISLOG=1 then the log spectrum is smoothed but in this study, ISLOG=0 and the amplitude spectrum is smoothed. As we shall see the optimum filter determined as discussed above was usually slightly outperformed by a fixed bandpass filter whose cutoff frequencies were determined by examination of several of the optimum filter shapes. This suggested that the optimum filter was somewhat unstable, not being averaged over a large enough time window. Therefore, the program also has the option that if ISUD=1, then in successive 10-minute windows the noise spectrum is recursively updated frequency by frequency, as is the LTA with the parameter ISIGS (analogous to ISIG), set equal to -2 in this study. As we shall see, with this modification the optimum filter slightly outperformed the bandpass filter when used in conjunction with the Z-log transform.

An option exists to compute the "Z" form of the STA/LTA detector. If IZ=1 then NDP calculates the "Z" variable which is given by (LTA-STA)/variance where the variance is estimated as the recursively updated value of $(LTA-STA)^2$ and where the time constant is taken to be the same as that for the LTA itself. If IZL=1 then the log of the STA is taken before the LTA and variance are computed.

For the Z detector the threshold is calculated on the assumption that the Z variable is normally distributed and so the threshold is computed via subroutine QUANTF which gives the threshold in units of standard deviations for a fixed probability of false alarm.

For the other detectors, when the STA is made up of squared filtered values (IASQ=1), then the STA is assumed to be distributed as chi-squared with 2BT degrees of freedom where T is the length of the STA, and B is the bandwidth of the filtered noise. B is calculated from the spectrum of the filtered noise by dividing the total power, (with the maximum of the smoothed spectrum normalized to 1), by the folding frequency. The spectrum may be further smoothed by IBWS, typically set equal to 15, before the bandwidth is computed. This second smoothing makes the maximum more stable and therefore stabilizes the estimate of the bandwidth. If a bandpass filter is used then the integral for the bandwidth is taken over the smoothed noise spectrum between the limits of the filter, (FLBW, FHBW).

Once the 2BT degrees of freedom have been calculated then the threshold is calculated using an inverse chi-squared routine, CHINV.

If a calculated threshold is not giving the desired false alarm rate, then it may be multiplied by the factor THDDL. This factor is generally in the range 0.9 to 1.1.

DISCUSSION OF RESULTS

In Table I and Figure 1, we see details on the results of running various of the program options discussed in the preceding section on the Pinedale detection tape which was put together in the manner described in Appendices I and III. Run 1 is the "benchmark" discussed in Appendix III and in the comments field in Table I we see an indication of the parameters specifying this run. (In general terms, the parameters for any given run are the same as those for the run immediately above it in the Table except for those which are noted. Also, unless otherwise specified, parameters will have the values indicated in the previous section as "usual in this paper.") Thus, the benchmark run number 1 squares the data before forming the STA, has a short-term average of 1.8 seconds, and requires 3/3 values of STA/LTA over the detection threshold which is determined by χ^2 with 2BT degrees of freedom and adjusted by the factor 0.85.

To best get an overview of the relative performance of the detectors, it is useful to plot them on a graph presenting both false alarm rate and probability of detection or threshold. The usual presentation is false alarm rate versus probability of detection for a fixed signal to noise ratio; this is termed the receiver operating characteristic (ROC). However, in this study, we choose another display, that of false alarm rate versus relative magnitude threshold. The false alarm rate and criteria for detection are determined as discussed in Appendix II, page 2, paragraph 4. The relative magnitude threshold is determined first by adding up the detections. A corrected number of detections is then determined by subtracting an estimate of the number of detections which are probably false alarms. This is determined approximately as the false alarm rate times the total signal windows in which a detection is not expected to occur. These signal windows are taken to be those in the 3rd and 4th S/N level, plus 1/2 of those in the 2nd S/N level. Thus, for Pinedale, with a total of 124 signal windows, the expected number of false detections for case 1 is (2.5/4) x 124 x (.5/60) x (F/HR) = 3.81. The (0.5) comes from the fact that the signal window is 0.5 min. The F/HR = 116/(9.5 x 124/60) = 5.9. Thus, the corrected number of detections is 42 - 4 = 38.

To convert this into a relative magnitude estimate we first note that the average difference in S/N between S/N levels is 0.3 magnitude units since the signal levels are decreased by a factor of 2 for each step.

Thus, if detector 1 detected each signal to one lower level than detector 2, we would have no hesitation in saying that detector 1 was 0.3 m_b units better. Now, there are about 30 signals per magnitude level so that we are immediately tempted to say that if detector 1 detects one more event than detector 2, then it is .3/30 = 0.01 m_b units better.

This is, in fact, the interpretive approach we shall follow and we may further justify it as follows.

Even if all of a set of signals and noise have exactly the same long-term stochastic S/N, the fluctuations of the noise process guarantee that there is neither perfect detection nor perfect non-detection at a fixed false alarm rate. In fact, Blandford and Wirth (1973) showed that one could characterize a particular automatic power detector as if it were an infinitely sharp detector as a function of S/N but that the S/N ratio varied with a standard deviation of 0.092 m_b units. Thus, even if all "true" S/N values are exactly the same, an improvement in the detection threshold will result in a few more events being detected. For example, in the case where for detector 1 the threshold is 0.15 m_b below the fixed (S/N) we would expect to get $Q(\frac{.15}{.092}) \times 30 = 1.5$ events. If the threshold were improved using detector 2 by 0.1 m_b, then we would expect to get $Q(\frac{.05}{.092}) \times 30 = 9.3$ events for a difference of 7.8 events, almost equal to the 10.0 we would get if the S/N values were distributed uniformly. (Here $Q(x) = 1 \int_0^x Z(x)dx$ where $Z(x)$ is the unit normal).

In fact, we do not expect that the S/N values for all signals in an S/N level are the same. The signal spectra change in shape from event to event, the signal lengths change, thus changing the S/N in a fixed window length, and the noise spectra change as a function of time. Thus, it seems reasonable to assume that within any given S/N level there is a rather broad distribution of "equivalent" S/N values that, when convolved with the detector response for fixed S/N as discussed above, results in an additional event detected for each .01 m_b improvement in threshold.

TABLE I

This table gives the parameters and principal results of the detection runs performed by the authors. The successive columns give the run number, the identifying name of the run of program DPP which appears on the computer printout, the month and day of 1980 on which the run was made, and four columns giving the number of false alarms and detections in each of the four S/N bands. The seventh column is the sum of the preceding four.

In the comments column , the only parameters which are given are those which change from the preceding run. 0 stands for the optimum filter, 1-2 Hz or 1-1.5 Hz signify the appropriate bandpass filter, SM signifies the optimum smoothed filter. χ^2 threshold signifies that the threshold was determined separately for each 10-minute window using χ^2 statistics, Z and Z-log runs have the threshold determined by the unit normal. D is an adjustment factor to a computed or fixed threshold to modify the false alarm rate. S is the STA time in seconds, and 1/3 or 3/3 signify the Q/Q' parameters. If Q/Q' = 3/3, then the effective value of the STA is ~ 5/3 times the stated value. V is the fixed turn on threshold for STA/LTA detectors. The remaining parameters are self-explanatory or are detailed in the text.

TABLE I

Pinedale

	Name	Date M/D	FA/D 1/2	FA/D 1/4	FA/D 1/8	FA/D 1/16	Σ	Comments
1	PWY10PSA (std)	7/2	17/28	27/14	43/3	29/2	116/42	0, a^2, χ^2 threshold, S=1.8 (3), 3/3. D=.85
2	PIT2IBMA	7/23	16/27	19/10	19/4	19/0	73/41	1-2 Hz, $\|a\|$, V=1.85
3	PIT2IBMA	7/22	56/30	56/14	66/8	77/5	255/57	V=1.7
4	PIT2IBMS	7/23	26/28	30/11	24/4	30/0	111/43	a^2, V=3.0
5	PIT2IBNS	7/22	14/27	23/9	24/4	16/0	77/40	V=3.2
6	PIT1P5MS	7/23	21/26	21/11	34/5	28/2	104/44	1-1.5 Hz, V=4
7	PI03	7/1	9/27	19/13	30/4	22/2	79/46	0, χ^2 threshold, D=.9, S=3, 1/3
8	PI03P85	7/12	12/27	22/12	28/5	19/3	81/47	D=.85
9	P3P78	7/12	28/29	34/16	48/6	37/4	129/55	D=.78
10	PI010	7/13	20/31	21/14	23/4	18/4	82/53	S=10 D=1.0
11	PI030	7/1	25/25	19/16	31/3	25/6	100/50	S=30 D=1.05
12	PI030TSO	7/1	36/22	23/12	29/2	30/6	118/42	t*=0
13	PIOSNEQO	7/13	19/28	25/14	24/4	17/5	85/51	t*=.3, S=10, D=1.0, S/N^2 ($S << N$)
14	P10F1SN	7/13	53/23	42/7	38/2	46/3	179/35	1/N (prediction error)
15	P10FWE1N	7/13	12/29	13/14	14/2	11/1	50/46	$S^2/(S^2 + N^2)$(Weiner)
16	PIOWNP		39/30	48/16	55/5	39/7	181/58	D=.9
17	PSTD3	10/22	16/23	18/10	23/3	19/2	76/43	Same as (1) except smoothed filter (SM) and smoothed spectrum for χ^2 threshold
18	PIT2I10S	7/25	19/31	24/14	27/5	24/3	94/53	S=10, 1-2 Hz, a^2 V=1.85
19	PIT2I10A	7/25	22/30	27/13	30/4	23/3	102/50	$\|a\|$
20	PIT210Z	10/1	38/31	40/16	33/5	39/4	150/56	a^2, Z, D=1.3
21	PIT210ZL	10/1	38/31	38/15	28/6	42/6	136/58	Z log, D=1.0
22	PIT2TZL1	10/2	19/31	21/12	19/4	25/3	84/50	D=1.1
23	PIT210Z4	10/2	22/31	27/15	25/4	28/4	102/54	Z D=1.4
24	PS3	10/22	15/30	13/11	24/5	19/3	71/49	Same as 7 except SM and D=1.0
25	PS10P1	10/22	12/31	13/12	15/2	10/2	50/47	S=10, D=1.1
26	PS30P05	10/21	23/26	18/15	30/3	26/5	87/49	S=30, D=1.05
27	PSTP9C1X	10/22	16/31	13/13	16/3	21/4	66/51	S=10, D=.9, f_c =1.0 3/3
28	PSTP1CQ$_1$	10/24	17/30	18/13	22/4	19/4	76/51	f_c=2.0, D=1.05, 1/3
29	PS10	11/03	28/30	30/13	30/6	30/5	118/54	Same as for 25, D=1.0
30	PSP9T1T2	11/03	21/31	26/14	30/4	22/3	99/52	1-2 Hz, χ^2 threshold, D=.9
31	PSTZL	11/04	17/31	12/16	24/3	20/8	73/58	Z log, D=1.0
32	PSTZ	11/05	27/31	23/13	27/4	24/6	101/54	Z

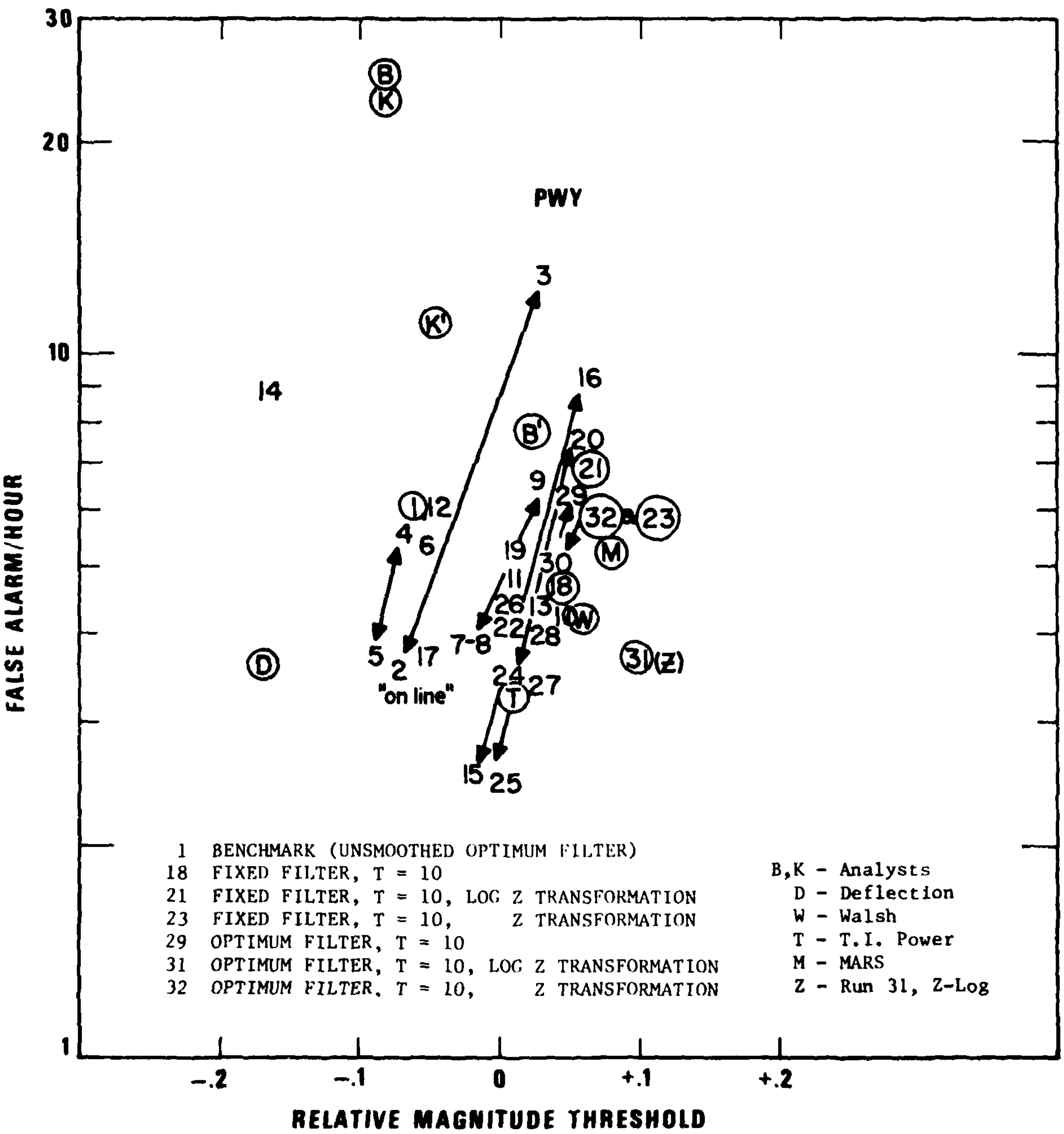

Figure 1. False alarm versus relative magnitude threshold for different detection on Pinedale test tape.

Pinedale Data

In Appendix V are presented plots of the signal windows together with the original signals before they were buried in the noise. In Table I we see the results from the different runs, and in Figure 1 each run is represented as a point in a plot of corrected false alarm rate per hour versus relative magnitude threshold. Zero magnitude threshold corresponds to a corrected number of detections equal to 46. Run number 1 is the benchmark run discussed in Appendix III. We see in Figure 1 that since it has a low relative magnitude threshold for a typical false alarm rate that it is actually one of the poorer detection systems studied in this report. (Even so, however, it is only about 0.18 m_b worse than the best.) The points connected by lines are pairs of runs which differ only in the threshold setting. Thus, they define a curve such that as the magnitude threshold improves the false alarm rate increases. For example, the line connecting runs 2 and 3 represents a threshold change from V=1.85 to v=1.7 for a 3/3, 1-2 Hz filter, absolute value, 1.8 second STA detector. We see that the lines drawn do not cross each other and are fairly parallel so that on an empirical basis it is possible to say that if point A is to the left of a line with such a slope drawn through point B, then the line through A represents a better detector.

We may first discuss whether a window of 3, 10, or 30 seconds is best for detection. One might anticipate that 10 seconds would be best because inspection of the signal length estimates in Table II of Appendix III shows that they are fairly uniformly distributed between 3 and 30 seconds. That 10 seconds is best may be seen by comparison of runs 8, 10, and 11 which are identical except that they are for 3, 10, and 30 second STA windows respectively.

These are optimum filter runs without smoothing and with threshold determined by automatic χ^2 calculations. We see that the 10 second window is about 0.05 m_b units superior to either of the other two. In other calculations we have found if we knew which signal was coming in advance, then using exactly the right window does convey an advantage of about 0.1 magnitude units. In the absence of such information, then the proper thing to do is to pick a middle value. Comparison of runs 24, 25, and 26 show the same effect although the absolute difference is only on the order of 0.03 m_b units instead of 0.05. The difference is probably within the range of statistical fluctuations for these calculations.

One may then ask which of several filtering procedures is optimum. For this we may compare runs 10, 13, 14, and 15 which use, respectively, the optimum filter for the case S/N=1 at the maximum value of S/N; the optimum filter for the case S/N << 1; the prewhitening filter 1/N, optimum if S/N >> 1, and otherwise known as a prediction error filter if causal; and finally, the Weiner filter $S^2/(S^2 + N^2)$ for the case S/N=1 at the maximum value of S/N.

From inspection of Figure 1 it is easy to see that the prewhitening filter is about 0.25 m_b inferior to the other three filters. Of the remaining three the optimum S/N=1 filter is about 0.02 m_b superior to the other two. It was a bit surprising that the Weiner filter performed so well; perhaps for cases where there is better S/N at high-frequencies where the signal spectrum is not flat, then the "extra" S in the Weiner numerator will degrade the Weiner filters' performance.

Along the line of the optimum filter there is also the question of the optimum signal spectrum. Again, in practice, one would wish to find the spectrum of the expected observations. Typical values of t* are in the range 0.1 to 0.5 and for this run we have chosen 0.3. To compare to another choice of t*=0.0 which might be suitable for P_n at distances up to 10° we may compare runs 11 and 12. Here we see that for this data base, which consists predominantly of teleseismic P waves, the t*=0 spectrum is about 0.06 m_b units worse than the t*=0.3.

For small events the optimum source spectrum for P waves is no doubt a flat one. However, Figures 2 and 25 in Sobel and von Seggern (1978) show that for the m_b=5 level events which have been scaled down in this study a corner frequency of 1.0 Hz is typical. Thus, it seems reasonable to try detection, assuming a corner frequency of 1 Hz. In this case we may compare run 25 which has the standard flat spectrum (corner frequency around 20 Hz) with run 28 with a 1 Hz corner frequency. We see that it is less than 0.01 m_b superior, an undetectable amount. In any event we would not use a 1 Hz corner frequency in practice since we are trying to detect small events, not big ones.

As to whether 1/3 is superior to 3/3 in detection, it would appear that it is, for 3-second windows. This may be shown by a comparison of runs 5 and 7 which are identical 3-second detectors except in that respect. We see from Figure 1 that the 1/3 is approximately 0.07 m_b units better which is probably a reflection of the general superiority of "incoherent" detectors to voting detectors as discussed by Wirth et al (1976). In the 1/3 detector, a single 3-second window is tested, whereas in the 3/3 detector, a 1.8 second window is slid along in increments of 0.6 seconds and 3 consecutive detections are required, a kind of voting procedure over a total of 3 seconds.

We may also ask if taking the absolute value of the filtered data for the STA is worse than the theoretically optimum procedure of squaring the data. Comparison of runs 2 and 5, and 18 and 19 in Figure 1, shows that for the average of the two cases, squaring is superior by about 0.01 m_b units, but one could not reject the hypothesis that there was no significant differences, the same conclusion reached by Vanderkulk et al (1965) and Husebye (1972).

One may see that the threshold is not very sensitive to the precise recursive filter bandpass by comparing runs 4 and 6 which have, respectively, a 1-2 and 1-1.5 Hz filter. It would appear that the 1-1.5 filter is about 0.01 m_b units superior to the 1-2 Hz filter, a difference which is probably not significant.

We may also evaluate the "Z" detector as discussed by Shensa (1976). We shall evaluate only the broad-band version in which the filtered data is transformed into a normal distribution using a mean (LTA) and variance recursively computed value of $(\text{STA-LTA})^2$. In the present program the constants for the recursive calculation of the variance are the same as for the calculation of the LTA. The threshold is calculated using a subroutine for the inverse of the normal distribution (QUANTF). The Z transformation is performed if the program parameter IZ=1. If IZL=1 then the log of the STA is computed before the remaining statistics are computed. By comparison of bandpass filtered runs 20 and 23 with 21 and 24, we see that taking the log does not seem to improve the threshold. The run that corresponds to the same processing but using a fixed threshold on the simple STA/LTA is run number 18 and we see that it is equal in capability to the Z transform result, suggesting that the transformation does not further enhance detection capability when used in conjunction with a fixed filter. However, as we shall see, the transformation does keep the false alarm rate constant (as do the χ^2 statistics), and it seems to enhance the capability of the optimum filter as we see below.

Run number 25 uses the optimum filter and a 10-second STA with the variable threshold computed from χ^2 statistics with 2BT degrees of freedom. When compared to the optimum filter using the log Z transform we see the transform is about 0.07 m_b units better. Thus, we conclude that the Z transform neither helps nor hurts detection capability for fixed filters, but together with optimum filters the z-log transformation offers a significant advantage. The reason for this is unknown at present.

To examine the false alarm rate question in more detail we give in Tables II-1 and II-2 the false alarms occurring for the Pinedale tape in 10 consecutive 2-hour windows. Since detections in 30 seconds of each 10-minute window are classed as detections and not false alarms, the numbers given are actually the number of false alarm detections in 1-hour and 54 minutes.

Table II-1 is for run number 18, the best recursively filtered trace; a fixed threshold operating on a 10-second squared STA out of a 1-2 Hz fixed recursive filter with detection declared on a single threshold crossing.

Assuming that the number of false alarms in a window is a Poisson process with parameter λ equal to the average number of detections over the whole tape one cannot reject the hypothesis that the false alarm rate is constant with 90% confidence except for the first window. For this case one or zero detections is expected to occur in 10 tries with < 0.01 probability; thus we might conclude that the false alarm rate <u>is</u> varying for this case. In Table II-2 we see the results for run 31 the log Z transform coupled with the optimum filter. Here we see no evidence of a non-constant false alarm rate, as would be expected from the design of the detector.

<u>NORSAR Data</u>

Analysis of the NORSAR data, discussed in Appendix II, yields generally the best result; this result is only slightly better (~ 0.03 m_b) than the same procedure using a 3-second window (16), but much better (~ 0.1 m_b) than a 30-second window (22).

TABLE II-1

FIXED FILTER PWY (RUN 18)

S/N	1/2		1/4		1/8		1/16		F/2 HR	
	F	D	F	D	F	D	F	D		
#										
1	1	1	0	0	0	1	0	0		
2	0	1	0	1	0	0	0	0		
3	0	1	0	1	0	0	0	0	1	prob $\leq$ 1 in 10
4	1	1	1	0	2	0	0	0		times < .01
5	1	1	0	0	3	0	0	0		
6	1	1	0	0	4	1	1	0	14	
7	0	1	5	1	1	1	1	0		
8	0	1	1	0	1	0	1	0		
9	1	1	1	0	2	0	1	1	15	
10	0	1	1	0	0	0	1	0		
11	0	1	0	1	0	0	2	0		
12	0	1	1	0	0	0	3	1	9	
13	1	1	1	1	1	0	1	0		
14	2	1	1	0	2	0	0	0		
15	0	1	2	1	3	0	2	0	16	prob $\geq$ 16 in 10
16	2	1	0	1	0	1	0	0		times > 0.26
17	0	1	0	1	0	0	0	0		
18	1	1	0	0	0	0	2	0	5	
19	0	1	0	0	0	0	0	0		
20	1	1	0	1	2	0	2	0		
21	2	1	1	0	0	0	1	0	9	
22	0	1	0	0	0	0	0	0		
23	0	1	3	1	1	1	0	0		
24	0	1	2	0	1	0	1	0	8	
25	2	1	1	0	1	0	1	0		
26	0	1	1	1	1	0	1	0		
27	0	1	0	0	0	0	0	0	8	
28	2	1	0	1	0	0	0	0		
29	0	1	1	0	0	0	2	1		
30	1	1	0	1	2	0	1	0	9	
31	0	1	1	1	0	0	0	0	F/D	F/HR/D_c
	19	31	24	14	27	5	24	3	94/53	4.7/50

TABLE II-2

OPTIMUM FILTER, LOG Z PWY (RUN 31)

S/N	1/2		1/4		1/8		1/16		F/2 HR	
	F	D	F	D	F	D	F	D		
1	0	1	0	0	0	0	1	0		
2	0	1	0	1	2	0	1	0		
3	0	1	0	1	0	0	0	0	4	prob ≤ 4 in 10
4	1	1	1	1	1	0	0	0		times > 0.7
5	0	1	0	0	1	0	0	0		
6	0	1	0	0	3	0	0	0	7	
7	1	1	1	0	0	0	0	0		
8	1	1	1	1	1	0	0	0		
9	0	1	0	0	0	0	1	1	6	
10	0	1	0	0	0	0	0	1		
11	0	1	1	1	1	0	1	1		
12	0	1	1	0	0	0	2	0	6	
13	0	1	1	1	0	1	1	0		
14	1	1	0	0	0	0	1	1		
15	1	1	1	1	2	0	1	0	9	
16	1	1	0	1	2	1	0	0		
17	0	1	0	1	0	0	0	0		
18	3	1	0	0	2	0	1	1	9	
19	0	1	1	0	1	0	0	1		
20	1	1	0	1	3	0	0	1		
21	1	1	0	0	1	0	1	0	9	
22	1	1	0	1	0	0	1	0		
23	0	1	0	1	1	1	1	0		
24	1	1	1	0	1	0	0	0	7	
25	0	1	0	1	0	0	2	0		
26	1	1	0	1	1	0	1	0		
27	0	1	1	0	0	0	0	0	7	
28	0	1	0	1	0	0	0	0		
29	1	1	1	0	1	0	2	1		
30	1	1	0	1	0	0	1	0	7	
31	1	1	1	0	0	0	1	0	F/D	F/HR/D_c
	17	31	12	16	24	3	20	8	73/58	3.7/56

TABLE III

NORSAR

	Name	Date M/D	FA/D 1/2	1/4	1/8	1/16	Σ	Comments
1	NORSTD	6/6	43/28	35/16	45/4	41/2	104/50	t*=.3 , a^2 S~ 1.5, 3/3
2	NORIBM	7/10	10/25	5/13	8/5	11/0	34/43	1.5-4 Hz, $\|a\|$, S ~ 1.8, v=1.75
3	NIBM1P6	7/11	52/27	32/20	46/9	59/8	189/64	v=1.6
4	NORIBMS	7/10	34/28	31/21	38/8	48/4	151/61	a^2 v=2.45
5	NIO3	7/9	16/24	11/11	12/3	14/2	53/40	t*=3, 0, χ^2 threshold, S=3, 1/3,
6	NIO3P9	7/10	30/27	29/14	33/4	28/2	120/47	D=.9
7	NIO3P85	7/12	51/26	43/16	51/6	50/4	195/52	D=.85
8	NIO10	7/9	35/27	29/13	32/6	27/3	123/49	D=1.0, S=10
9	NIO30(B)	7/9	50/25	49/16	51/11	41/8	191/60	S=30
10	NIO30P05	7/12	26/23	20/15	25/7	24/2	95/47	D=1.05
11	NIO30TSO	7/10	25/17	27/11	15/8	18/5	85/41	D=1.0, t*=0
12	(5) + (11)	(7/9, 7/10)	36/24	31/14	32/6	34/6	133/50	"Regional plus teleseismic" not better than (8) for this tape
13	NIT4BT18	10/9	10/25	6/15	5/5	10/3	131/48	S=10, 1.5-4 Hz, v=1.8, 1/3
14	NIT43S26	10/13	28/26	10/18	25/7	29/4	92/55	S=3, v=2.6
15	NSTHTIT4	10/30	7/25	4/13	5/4	5/3	21/45	Auto threshold, SM, S=10
16	NS3ZL	10/31	18/28	6/18	12/8	15/3	51/57	Z-log, S=3, 0
17	NS3Q1	10/25	24/28	14/17	28/6	26/5	92/56	Flat source, D=1.0, 1/3
18	NS10ZL	10/30	16/27	17/20	14/11	21/5	68/63	Z-log detector, S=10, D=.95
19	NSP9TIT4	11/1	27/27	18/19	18/8	25/4	88/58	Fixed filter, smoothed auto threshold, D=.9
20	NS30Q1	10/31	53/23	49/19	44/9	50/7	196/58	S=30
21	NS10PQ1	10/24	20/28	15/19	13/7	20/7	68/57	S=10, D=1.05 fixed to B7
22	NS30ZL	11/1	25/23	37/19	29/10	41/8	132/60	S=30, Z-log
23	NIT4BT15	10/8	63/28	55/21	66/15	88/6	272/70	Same as for 13 with v=1.5 (S=10)
24	NIT4TI65	11/3	28/27	20/20	22/8	28/4	98/59	v=1.65
25	NIT4ZL	11/3	36/27	44/21	46/11	58/7	184/66	1.5-4 Hz, Z-log
26	NSTZ	11/5	15/28	15/18	13/7	23/4	66/57	D=1.4, SM, Z
27	NIT4TZ	11/5	22/28	22/20	17/7	26/4	85/59	1.5-4 Hz, Z

See Table I for a discussion of Table format.

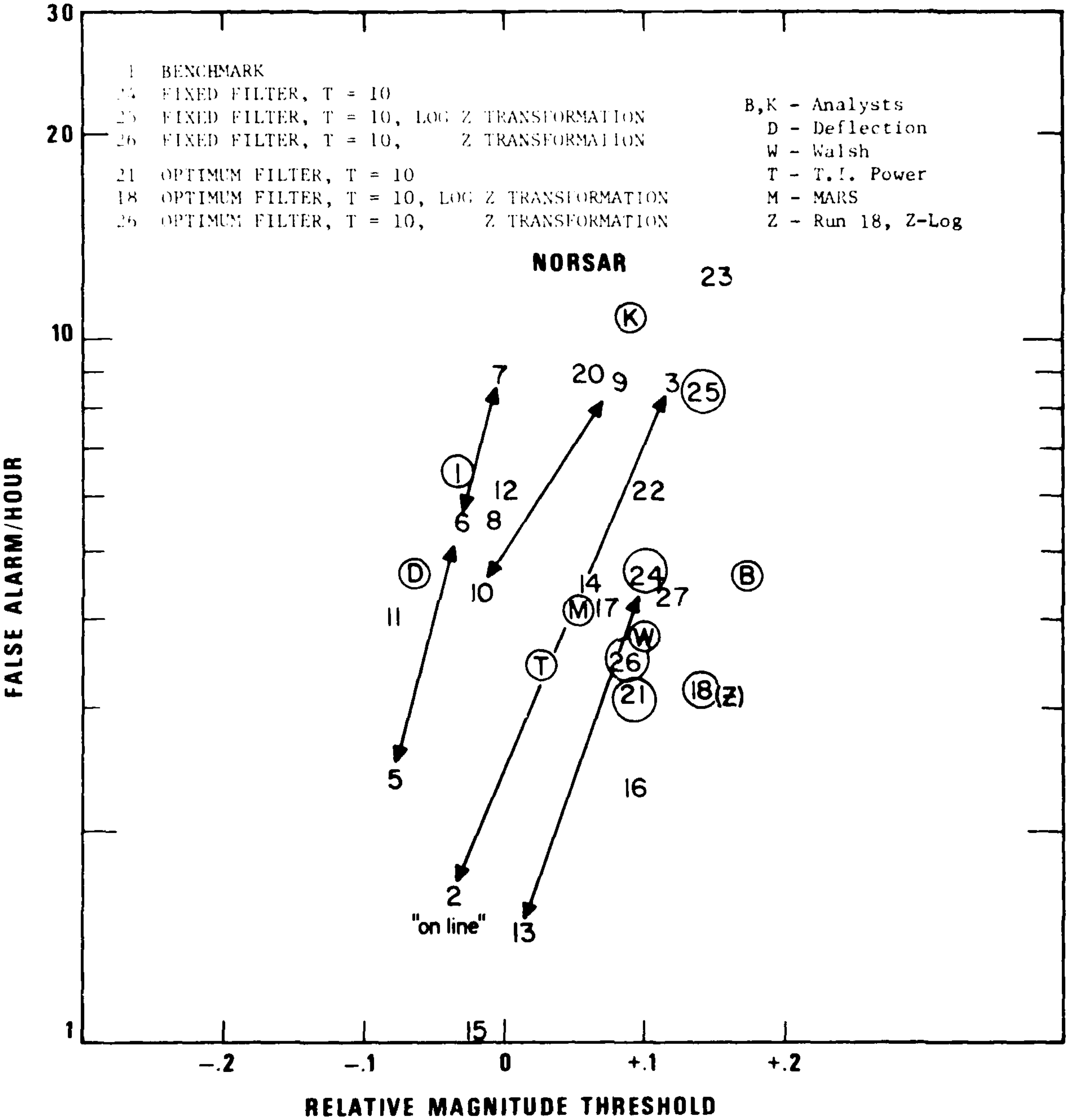

Figure 2. False alarms versus relative magnitude threshold for different detectors on NORSAR test tape.

TABLE IV-1

FIXED FILTER NORSAR (RUN 24)

S/N	1/2		1/4		1/8		1/16			
	F	D	F	D	F	D	F	D	F/2 HR	
#										
1	1	1	1	1	1	1	0	1		
2	1	0	2	1	1	1	1	1		
3	2	1	0	1	0	1	1	0	11	
4	1	0	1	0	0	0	2	0		
5	1	1	0	1	0	1	2	0		
6	0	1	1	0	1	0	0	0	9	
7	0	0	0	0	1	1	0	1		
8	2	1	1	1	2	0	0	0		
9	1	1	1	1	0	0	0	0	7	
10	0	1	0	1	2	0	1	0		
11	1	1	2	1	0	0	0	0		
12	0	1	1	1	0	0	1	0	8	
13	2	1	1	0	0	0	1	0		
14	1	1	0	1	2	0	0	0		
15	2	0	0	0	0	0	1	0	10	
16	0	1	1	1	0	0	0	0		
17	0	1	0	0	0	0	1	0		
18	0	1	1	0	1	0	1	0	5	prob 5 or
19	0	1	0	0	1	0	5	0		less in 10
20	1	0	0	0	2	1	0	0		times >0.7e
21	1	1	0	1	0	0	0	0	11	
22	0	0	1	0	0	0	1	0		
23	0	1	1	1	0	0	1	0		
24	1	1	0	0	1	0	1	0	7	
25	0	1	1	0	0	0	0	0		
26	2	1	1	0	0	0	1	0		
27	2	1	0	1	0	0	1	0	8	
28	2	1	1	1	1	0	2	0		
29	0	1	0	1	3	1	0	0		
30	0	1	0	1	1	0	0	0	10	
31	1	1	0	1	0	1	1	0		
32	1	0	0	0	1	0	0	0		
33	1	1	1	1	1	0	0	0	7	
34	1	1	1	1	0	0	3	1	F/D	F/HR/D_c
	28	27	20	20	22	8	28	4	98/59	4.5/56

TABLE IV-2

OPTIMUM FILTER, LOG Z, NORSAR (RUN 18)

S/N	1/2		1/4		1/8		1/16			
	F	D	F	D	F	D	F	D	F/2 HR	
#										
1	1	1	0	1	1	1	0	1		
2	1	0	2	1	1	1	0	1		
3	2	1	0	1	1	1	0	0	9	prob 9 or
4	1	1	0	0	1	0	1	0		more in 10
5	1	1	0	1	0	1	1	0		times >
6	1	1	0	0	0	0	1	0	7	0.9
7	0	0	0	0	0	0	2	0		
8	1	1	1	1	1	0	0	0		
9	0	1	1	0	0	0	0	0	6	
10	0	1	0	1	1	0	1	0		
11	1	1	1	1	0	0	1	0		
12	0	1	1	1	0	1	0	0	6	
13	1	1	1	0	0	0	0	0		
14	1	1	0	1	2	0	0	0		
15	0	0	0	0	0	1	0	0	5	
16	0	1	1	1	0	0	1	0		
17	0	1	0	0	0	0	3	0		
18	0	1	1	0	1	1	0	0	6	
19	0	0	0	0	0	0	2	0		
20	0	0	0	0	2	0	0	0		
21	1	1	0	1	0	0	0	0	5	
22	0	0	2	1	0	0	0	0		
23	0	1	0	1	0	0	1	0		
24	0	1	0	0	0	0	1	1	4	
25	0	1	1	0	0	0	2	0		
26	1	1	2	1	0	0	0	0		
27	1	1	0	1	0	0	1	1	7	
28	1	1	1	1	0	0	1	0		
29	0	1	0	1	2	1	0	0		
30	0	1	0	1	0	1	1	0	6	
31	0	1	2	0	0	1	0	0		
32	0	0	0	0	0	0	1	0		prob 3 or
33	0	1	0	1	0	0	0	0	3	less in 10
34	1	1	0	1	1	1	0	1		times >0.67
									F/D	F/HR/D_c
	16	27	17	20	14	11	21	5	68/63	3.1/60

The standard "benchmark" run (1) is about 0.2 m_b worse than the optimum due in part to the instability of the optimum filter.

Comparing runs 2 and 4 there is again no detectable advantage to squaring over taking the absolute value, despite the theoretical result that squaring is the preferred procedure.

The best detector which does not use the Z log transform is run 21 which uses the fixed 1.5-4 Hz filter, a 10-second window, squaring and a 2BT threshold. It is about 0.05 m_b units worse than the best.

COMPARISON WITH WORK BY OTHER CONTRACTORS

In Figures 1 and 2 we have presented data points from several other detectors, human analysts (B, K), the MARS process (M), Farrell et al (1980), the Texas Instruments power detector (T), the deflection detector (D), and the Walsh detector (W), in those same figures the Z-log detector operating on a 10-second window as discussed in the preceeding section is designated by the letter Z. Detections by these processors are plotted on the signal windows in Appendices V and VI.

In this section, we briefly describe each of these detectors and make some comparisons between them.

The results for the human analysts (Richard Baumstark and Raymond Kimmel, with over 20 years AFTAC, LASA and NEP analysis experience between them) were obtained as follows. The data were plotted out at develocorder scale on a Calcomp (the same scale as seen in Appendices V and VI) only one trace on the page, in windows of random lengths ranging from 5 to 10 minutes. The program ensured that a signal did not begin in the first or last 30 seconds of a sheet. The analysts were informed of the method of plot construction and were asked to analyze the plots in random order so that they could not "predict" by patching plots together where a signal would occur. The analysts were told that there would be one or zero true signals per plot, and that they should try to make fewer than three calls per plot. The analysts, generally speaking, found the plots difficult to analyze but thought that the presentation was "fair"i.e., not biased against them, except possibly for the high-frequency noise at PWY which comes from the transformed quantization noise. In Figure 1 the letters B and K show that the analysts liked to operate at a very high false alarm rate so that although they detected as many true signals as tne best detectors, their high false alarm rate leads to an estimate that they are 0.2 to 0.3 m_b units worse than the best detector at a fixed false alarm rate. They appear to be close in capability to the prediction error filters, a result in agreement with von Seggern (1977) who studied prediction error filters to see if they were suitable as first motion detectors. After the analysts had analyzed the NORSAR plots, they were asked to return to the PWY plots and reduce their false alarm rate by discarding those detections they were less sure of. This resulted in substantial improvement in performance (see B', K' in Figure 1), simultaneously reducing the number of false alarms and increasing the number of "true" detections. (Of course, the actual number of detections decreased by (9, 10); however, this was overcome by the reduction in estimated false detections due to the decrease in the false alarm rate.) This change in performance is a reverse slope to the trend of performance of every other detector discussed in this paper as the threshold is varied and suggests that the human qualitatively changes the type of processing as his "threshold" changes and does not simply look for a larger value of some parameter. For example, the analyst may require "duration" in addition to "frequency change" if he wants to be more certain instead of looking simply for a greater value of "frequency change."

In Figure 2 for NORSAR, the analysts are in the midst of the performance points for other detectors and in fact one performance is as good as the very best automatic detector. In this case, the analyst reports near-ideal peaceful conditions at home for the analysis, and that he was able on this, and some other occasions, to get in the groove of the analysis.

These results suggest that under routine operational conditions with develocorder film, time for accommodation, a peaceful environment, and interest in the work, a trained human analyst can be at least the equal of an optimum detector in pure detection of teleseisms. However, these conditions are severe ones and in production one might expect the machine to outperform the analyst. It is important to note, however, that pure detection is only a part of the analyst's job. They must also discard detections of noise, e.g., instrument noise, lightning, electric discharges, glitches, machinery noise, locals, etc; and must detect in the presence of other events. Thus, in a practical sense, operations within 0.1 m_b of the optimum as indicated in Figures 1 and 2 for the "on-line" system is generally satisfactory until the serious practical problems mentioned have been solved.

This result, that automatic detectors are qualitatively equal in pure detection to the analyst, has been the general understanding of the SDAC analysts who worked on LASA, and on NEP after the DP software bugs had been fixed.

Examination of the plots in Appendices V and VI show that the analysts' time picks are generally more accurate than those of the other detectors. (However, of the plotted detectors only the MARS processor exercised an option to compute a refined start time--which was plotted in the Appendices--; thus strictly speaking, detection time comparisons should not be made.) In fact, the analysts so often picked a few seconds early that 10 seconds in front of the signal was allowed to count as a detection on the theory that the analysts detected late and "backed up" to an incorrect start.

The TI power detector (T) is based on results provided to us by J. S. Mott of ENSCO, Florida. The detector is basically that of a Z-log detector with a fixed filter. The bandpass filter for PWY is 0.6 to 2.0 Hz, and the STA length is 9.6 seconds. It is, therefore, most similar perhaps to our PWY run 21, and in fact, it seems to lie near the same detection curve. The NORSAR filter is a 0.8 Hz high-pass filter followed by a 6 dB/octave high pass. The combination is down by 6 dB at 1.5 Hz and so is comparable to our 1.5-4 Hz filter. It is similar to our run 25 and does indeed seem to lie on the same detection curve.

The maximum deflection detector (D) is a qualitatively different type of detector also run by ENSCO in Florida. In this detector, after highpass filtering to remove the microseisms, an FFT is taken of successive 3.2 second windows and the window is slid one second at a time. Selected individual periodogram values in the signal "frequency window" (.93-3.86 Hz for PWY, .93 to 2.48 Hz for NORSAR) are tracked as a function of time by incorporating them into the "Z" variable form. A high threshold of 5.0 is set on each Z value and if for any single frequency there is a detection then a system detection is declared.

As discussed in Appendix I, this is a type of voting detector (Wirth et al, 1976), which on theoretical grounds is expected, all other things being equal, to be inferior to an appropriate broadband detector. Furthermore, by allowing a detection if only 1 out of N frequencies detect instead of K out of N with $K > 1$ it is probably not even an optimum voting detector. (The MARS detector is similar to the deflection detector, has K=5, and shows better performance.)

In fact, we see in Figures 1 and 2 that the deflection detector is one of the least successful detectors, although it does out-perform the human analyst in some cases. This points up the difficulty of detailed calibration of automatic detectors by comparing them to analyst picks on real data.

The MARS processor, Farrell et al (1980), first takes in a window of about 100 seconds; they are tapered by 10% and Fourier transformed. The frequency range of 0.25 to 5.0 Hz is split into 20 bands with spacing approximately equal to ~ 5./20 = .25 Hz. The width of the filter applied to each band is, however, ~ .08 Hz so that the time constant of such a filter is approximatley 1/.08 = 12.5 seconds. Thus MARS is operating with a ~ 10 sec integration time as was found to be suitable in our earlier analyses. The envelope of the narrow band is calculated and statistics, mean and standard deviation, are kept of the distribution of the maxima. If 5 bands exceed 1.8 standard deviations in 2.8 seconds, a detection is declared. The result of this voting type detector are seen in Figures 1 and 2. For PWY, its performance was surpassed only by the Z detector, although many other detectors are close to it. However, for NORSAR it is surpassed in performance by many others. Perhaps this is due to the greater bandwidth of the NORSAR data where voting detectors may be at a greater disadvantage.

Finally, we may discuss the Walsh detector. In this case, there is a digital recursive prefilter to the data cutting out the microseism energy below 1 Hz. (This is required because of the large sidelobes of the Walsh transformation.) Thereupon the Walsh transform is made of 3.2 second data windows and the Walsh coefficients prewhitened with the average from the first 15 minutes of noise and summed. This value is compared with a multiple of a selected point on a cumulated histogram and detections declared. Thus, this is essentially a power detector following a high pass prefilter. The algorithm works very well. The requirement of recursive frequency prefilter, however, means that its computational requirements would be comparable to those of other standard detectors, all other system and programming language considerations being equal.

SUMMARY

As discussed in the abstract, most detectors can be modified to perform in a near-optimum fashion. Probably the log-Z plus optimum filter detector and its future enhancements will always be slightly (~ 0.05 m_b) better than the others since it is based on a well-understood statistical foundation. The subject of array detection is equally well-understood and has been implemented in practice at LASA, NORSAR and TFO. Future detection research should be concentrated on experimental studies of network detection and on post-processors which determine the nature of the received signal. For this work also there should be test tapes constructed as a test bed.

The comparability of the automatic detector's and the human analyst's thresholds points out how hard it is to determine "truth" against which automatic detection may be checked, in a steady data stream. Nonetheless, the analyst is the desired judge of a detector in an absolute sense. It is he who notices in the course of event analysis that the detector does not miss signals he would have called and it is he who notices that all the detections "show something" and that the detector does not deliver up to him many spikes and drop-outs. To achieve this status is mostly a question of engineering detail and not of theory. By these criteria, both the 1971 LASA DP and the current SDAC DP are successful in an absolute sense, although relatively, the results of this experiment suggest that they could be improved about 0.1-0.15 m_b.

ACKNOWLEDGEMENTS

We would like to thank W. Farrell, J. S. Mott, and C. Veith for supplying detection results.

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APPENDIX I

FEB. 1, 1980 VSC TECHNICAL NOTE 38, "EXPERIMENTAL DESIGN FOR DETECTOR EVALUATION: SINGLE CHANNEL DETECTORS"

by

Robert R. Blandford

TABLE OF CONTENTS

INTRODUCTION

In most detection systems of which I am aware there is eventually produced a single time trace on which a detection must be made, either by an analyst or computer program. (one exception to this rule is FKCOMB which searches ω-K space for an F-statistic maximum). Since there is still debate within the seismic community on the best way to perform this basic process, I propose that we first attack this problem, before proceeding to 3-component and array processing problems.

In general we do not know what the wave-shape of a signal is going to be so that match filters are impractical, but we usually have a better idea about the signal's amplitude spectrum S on either observational or theoretical grounds. The noise spectrum N can, of course be easily measured. Freiberger (1963) showed if both N and S are Gaussian, the Neyman-Pearson filter with the highest probability of detection for fixed false alarm rate is $S/(N(S^2+N^2)^{\frac{1}{2}})$. Note that for large S this becomes 1/N, a pre-whitening filter, while for small S it becomes (1/N)(S/N), a pre-whitening filter weighted by the signal-to-noise ratio. Note also that in neither limit is this the Weiner filter $S^2/(S^2+N^2)$ whose goal is not detection but best least-square estimation of the waveform. The <u>match filter</u>, optimum for completely known signal, is the small-S limit as is reasonable, i.e. S/N^2 where in this case S is complex.

Workers at IBM, Vanderkulk et. al (1965) were fully aware of this theory and designed their filters using the small S limit. They showed that under certain realistic assumptions a band-pass filter would be a good enough match for (1/N)(S/N) that less than .05 m_b units would be lost.

The Neyman-Pearson detector further consists of squaring and integrating over time T the output from the optimum filter. (The output (STA) in the absence of signal is distributed as χ^2 with 2BT degrees of freedom, where B is the equivalent bandwidth through the filter. In the presence of signal it is distributed as non-central χ^2). IBM (1965) investigated the effects which rectification instead of squaring, and exponential weighting instead of integration would have on the detection threshold and concluded that the difference was less than .05 m_b. Husebye (1972) came to the same conclusion. This is illustrative of a general theorem - "most plausible detectors are near-optimum". With these insights, IBM determined the detection band-pass to use at LASA, and for many years the detector worked to the satisfaction of seismic analysts. In my own mind the basic theory of seismic detection on a single channel has been closed since 1963 although "tuning" of the filters and integration times to special situations still seems to be a subject for research.

A BRIEF SURVEY OF SELECTED RECENT RESEARCH IN SINGLE-CHANNEL DETECTION

Gyoystdal and Husebye (1972) compared prediction-error filters to band-pass filters and concluded that a band-pass filter could always be found which would out-perform the prediction-error filter. This is not surprising since we saw in the Introduction that a 1/N filter (which is what prediction error filters attempt to achieve) are optimum only for large S/N, whereas (1/N)(S/N) is optimum for small (S/N). Further work in this field for detection purposes should determine an evolutionary filter of the form (1/N) (S/N) for a suitable-a-priori S.

LaCoss (1972) noted that the false alarm rate (FAR) fluctuated at NORSAR and developed rules for varying the threshold as a function of the STA variance to hold the FAR constant. The cause of this variation was that the noise field would become more or less peaked, resulting in a different bandwidth, B,; and thus in the Neyman-Pearson context the numbers of degrees of freedom 2BT of the χ^2 distribution - changed and the threshold had to change in order to keep the FAR constant. LaCoss did not cast the theory in this context but defined a stability parameter as the ratio of the STA mean to the STA variance. This can be seen to correspond to a measure of 2BT, and so is monotonically related to the FAR. Bungham and Husebye (1974) report that continuously varying the threshold with an empirically determined function of the stability parameter was successful in stabilizing the FAR and resulted in a .025 m_b improvement in detection threshold. Shensa (1977) and other workers at Texas Instruments squared the STA, which is the optimum process, and transformed the output into a normal distribution with a standard deviation which varied with time. (Note that this transformation is theoretically impossible if the original time-series are Gaussian). The attempt however seems to be successful in a practical sense. Secoy (1978) evaluated this detector on array beams and found it to be satisfactory (there were however, problems with spikes and dropouts). This detector may be said to be as "standard" as the IBM detector, and some normalization of this type seems to be a useful idea. Blandford (1974) found that an F-detector operating on a beam for one month also performed in agreement with theory and had no trouble with spikes, dropouts, local events or noise bursts.

Wirth, Blandford, and Shumway (1976) investigated the optimum methods of combining detections from several stations. They found that "voting detectors", e.g. declaring an event when, say, 3 out of 5 Alaskan stations detect; are slightly worse than "incoherent" detectors in which the STA values from each station are added together and detection is made on the sum. Ringdal, Husebye, and Dahle (1972) had found the same results experimentally comparing voting and incoherent detection at NORSAR. These results are relevant to single channel detection because one may consider multiple frequency bands as multiple independent stations. Thus detectors which break up the spectrum into multiple frequencies, detect on each one, and then declare final detections on the basis of some rule should always be out-performed by simple band-pass detectors. It might reasonably be thought that exceptions to this rule will occur when the signal spectrum, S, is very poorly known. However, the work of Wirth et. al. (1976), and by implication the work at NORSAR where signal variability is very high across the array, show that in this case the incoherent detector has truly a substantial superiority.

Shensa (1977) investigated three different single-channel detectors. The first was the deflection detector where successive spectra are taken of the time series and the amplitude at each frequency is tracked over time. The distribution of each frequency's amplitude is tabulated and by use of logarithms transformed into the unit normal. (Of course if the original data are Gaussian, each amplitude is distributed as χ^2 with 2 degrees of freedom which has a long tail and looks much like a log-normal distribution). Then if any frequency exceeds a threshold an event detection is declared. This amounts to a voting detector with a 1/N pre-filter. The second detector investigated by Shensa is a kind of incoherent detector called the average deflection power detector where the unit normals are averaged over a signal band. Because of the normalization, this might amount to detection with a 1/N per-filter followed by a bandpass filter, the same process as that devised by IBM (1965), and might work rather well. However, because of all the transformations carried out on the multiple χ^2 distributions, this equivalence cannot be confidently asserted. The third detector is that of simply summing the raw power in the signal band and then converting to a unit normal. This detector is the same as that immediately above without the noise whitening and is equivalent to the one evaluated by Secoy (1978).

Savino et. al. (1979) have discussed the MARS detector in which multiple narrow passband filters are calculated and coincidences in detection are sought on the Hilbert transform envelope of each output. This is similar to the deflection detector of Shensa (1977) and has the same weakness that detection on some number of traces declares an event; thus we have basically a voting detector. Another weakness is that the envelope in effect integrates over a time window of length $1/\Delta f$ where Δf is the filter width. There is no particular reason for this to be equal to the length of the signal T; over which one should integrate for optimum detection.

Allen (1978) developed a detector with a view to making it simple enough that it could be implemented in a microprocessor. His detector works on a linear combination of the squared signal and the squared signal derivative. Obviously, it may be impossible to work the frequency response of this process into the form $S/[N(N^2+S^2)^{\frac{1}{2}}]$ so that it cannot be an optimum detector. In particular, if there is a large noise peak, such as the microseism band, a prefilter will be needed so that the 6 db/octave due to the derivative function can have a chance to be used to advantage.

Another detector developed with an eye to microprocessors is that due to Herrin which uses the Walsh transform. Here too, a narrow noise peak can lead to problems because of the side-lobes of the Walsh function response to a pure sine-wave. Each of these last two detectors, however, comes with an impressive array of ad-hoc procedures for eliminating non-statistical false alarms such as dropouts, noise bursts, and spikes.

DETECTORS RECOMMENDED FOR STUDY

- The IBM detector should be evaluated in its routine form and while operating in an optimum fashion. Squaring should replace rectification. Signal spectra should be estimated for explosions and earthquakes of various sizes for the P and Lg phases, and combined with typical noise spectra to produce optimum $S/N(S^2+N^2)^{\frac{1}{2}}$ and (1/N)(S/N) filters. The integration time T should be adjusted separately for regional and teleseismic distances and the improvements achievable over the standard detector reported. As a final topic, N might be updated at regular intervals. Rapid updating in the presence of large events would yield optimum detection of mixed events, and of Lg in the presence of coda.
- The Z detector and possibly deflection detectors could be evaluated as examples of detectors with fixed false alarm rates and as examples of detectors which use the "Z" transform.
- The MARS Detector could be evaluated as an example of a voting detector.
- The Allen and Walsh detectors can be evaluated, with prefilters, to see how these non-optimum detectors perform. If they are close to the other detectors in performance then their simplicity may recommend them in those situations where an analog prefilter is available or not needed.
- The Allen Detector should be evaluated for installation in intelligent line interfaces (ILI's) since it has capability for rejecting spikes.

EVALUATION

I suggest that the performance test for these detectors be made up of real signals buried in real noise. The noise would, however, have been modified by scrambling the phase so that any real weak signals would be dispersed throughout an FFT window and would be very unlikely to cause false alarms.

The technique for creating signals buried in noise would be as follows:

Noise Generation

- A simple detector is run over the data and all signals are detected with S/N $\geq$ some fixed threshold.
- With these detections at hand, an analyst brings a first 4096 pt time segment up on the tektronix screen. Assuming that he sees no detection, and that the detector also detected none, he initiates a program which performs a 10% cosine taper on the data, Fourier transforms the results, assigns random values to the phase, re-inverts to the time domain, applies 50% cosine taper and stores the result in core.
- Skipping 2048 points into the raw data, the same process is repeated, and the result is added to the last 2048 points of the previous data. (In the overlap region note that the sum of the two cosine tapers is 1.0). The previous 2048 points are read out to the subset save tape.
- The process is continued, except that when there is a detection or drop out in the window, the previous time period is used. However, a new set of random phases is generated so that the noise does not repeat identically. Make subset individual seismograms 8192 points long - i.e. 13 min 39.2 sec long for NORSAR and 6 min 49.6 sec for PWY.
- The final result is a tape full of noise whose spectrum changes as does the real noise, but which has no signals in it.

Signal Additions

- Signals will be added every 13 min 39.2 sec* exactly on the second. Signals will be selected by scanning automatic detections with high signal-to-noise ratios on the same channel under consideration. One minute of signal preceeded by one minute of noise, the dividing line its to be chosen by the analyst, will be spun off to subset tape.

* Changed for tapes delivered, see Appendices II and III.

Signals are to be fully representative of locals, regionals and teleseisms with some special cases for shots.

- To add the signals to the noise, the analyst will skip 12 min 39.2 sec into the noise tape and add the signal at such a level ε that it could be easily detected at its maximum by an experienced analyst. Then the same signal will be added in 13 min 39.2 sec later at $\delta = 1/2$ this amplitude, and then again at 1/4 and 1/8. To make for a smooth transition of the noise, the signal window before adding will be tapered by a 25% cosine taper; and the noise tape will be multiplied by one minus the product of ε δ and the cosine taper, $(1 - \varepsilon\, \delta \cos)$ so that the mean square noise level does not increase through the signal window.

Other Features of the Test Tape

- We will put in a few cases of large signals, spikes, and drop-outs followed by small signals so that those workers who wish to test their ability to detect in the shadow of large events may do so, and so that diagnostics of "glitch" false alarms may be exercised if desired.
- We suggest 24 hours of data for 2 channels this will result in 2 X 104 test signals, 52 different ones at four amplitude levels each.
- Two channels, one with high microseisms; near the coast, and one with low microseisms would seem to make a good test.
- Regional events will be represented by both a P-wave and an Lg window since the two phases have, generally, greatly different spectra.

Suggested False Alarm Rates

Different false alarm rates are suitable for different requirements. If one is considering an isolated single element, then FAR=1/hour might be suitable. If one is considering a voting detector operating on, say, the Alaskan network, then a single element FAR of 1/minute might not be too high. We have found that for operating our on-line DP in conjunction with NEIS stations, that our automatic association program is not badly confused at a FAR of 1/(5 minutes). I suggest for this test, that we run at two different rates 1/(10 minutes and 1/(30 minutes). For this experiment we need a reasonably high rate so that we can be statistically certain that we are operating at the advertised rate. Only if each worker in the experiment runs at the agreed-upon FAR will we be able to compare the detectors' performance. Note that if more than one detector is used, e.g. for regionals and teleseisms, then each detector FAR must be divided by M where M is the number of detectors.

Suggested Immediate Time Schedule

By February 6 ship to all participants 4 hours of raw data from the two selected channels in the proper format, presumably SDAC subset. Along with this data we will send a list of analyst picks. These data should enable the various participants to tune up their programs to such a degree that when the test tape arrives it can be run through immediately.

By March 15, the test tape as discussed above can be ready; and within a week thereafter we could produce the "blind" tape.

Suggested Data Channels

For the data channel dominated by microseisms, I suggest the center element of the C3 subarray at NORSAR. We have several years of continuous data from this source at the SDAC, and thus there are plenty of explosion signals at regional and teleseismic distances to merge into the noise. The data is very high quality and is conveniently manipulated with software in-house on both the 11/70 and 360/44. The only drawbacks to this data are that it is at 10sps and that there is a sharp cut-off at 4.75 Hz. This is a slight drawback from the point of regional detection, but to me it seems that the many advantages outweigh the drawbacks.

For the data channel not dominated by microseisms, I suggest the on-line data which we receive on the DPS tape from Wyoming. This data has all the advantages of the C3 data and is at 20sps. I know of no drawbacks to this data source; one other advantage that it has over the C3 data is that we have continuous 3-component data also.

A few comments about the Alaskan Data in comparison to the NORSAR data. In general the Alaskan data does not have the high dynamic range of the NORSAR data, and it is filled with spikes from line discharges. Furthermore, it is not at regional distances from explosions of interest. Thus, despite the fact that the ALK data is at 20sps, it seems better to choose the NORSAR data.

SUGGESTED FUTURE WORK

- Follow up initial tapes with tapes with signals buried at random as a "blind" test.
- Work on tapes of real data and see how the automatic detectors compare to analyst picks, and how they deal with spikes, dropouts, etc.
- Develop tests for best detectors on week-to-month data segments.
- Investigate enhancements possible with 3-component processing, e.g.
    - incoherent detection regarding the channels as independent
    - detection of asymmetry in horizontal components with Smart detector. (The F-detector in the Smart processor is not reliable due to continuous presence of signal, the processor is more useful to determine azimuth).
    - variations on Remode (polarization filters)
- Investigate enhancements possible with array processing, (a comprehensive study of this type will require more powerful computers or an array processor) e.g.
    - beamforming
    - maximum-likelihood detection
    - F-detector
- Then we can repeat the whole show with LP.

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APPENDIX II

JUNE 6, 1980 GEOTECH MEMORANDUM FROM R. R. BLANDFORD,
"TAPE CONSTRUCTION AND BENCHMARK DETECTION RESULTS FOR NORSAR"

MEMORANDUM

TELEDYNE GEOTECH

ALEXANDRIA LABORATORIES

TO: Recipients of the 30 May 1980 VSC detection experiment tape

FROM: R. R. Blandford

DATE: 6 June 1980

SUBJECT: Tape construction and benchmark detection results

The noise data are from 24 May 1979 as transmitted by satellite at 10 sps from the center element of the C3 subarray at NORSAR and recorded at the SDAC. This day was selected to minimize data dropouts and system downtime. The data were plotted as a check. A FORTRAN computer program was written to create "artificial" noise which would have no signals in it. The program operated as follows.

A 4096 point data window is read in and checked for signals and data dropouts. If there are none, then the data are 5% cosine tapered, Fourier transformed, the phase at each frequency is assigned randomly, and the data are transformed back to the time domain. Then the noise is tapered with a full 50% taper and added to the previous window (which has also been tapered) with a 50% offset. Because the sum of the two 50% tapers does not yield a constant root-mean-square amplitude this fact is corrected for by multiplying the summed time series by an analytical function of time. The successive overlapped portions are read out to the final noise tape leading to a continuous random noise field whose spectrum and amplitude vary smoothly as does the true noise field.

The next step in the process is to add in the signals. In Table 1 we list the signals used. Signals 1 and 2 are P and Lg from the nuclear explosion closest to NORSAR. Figure 1 shows the P signal and its spectrum from the original 20 sps high-rate data. This is the raw spectrum uncorrected for instrument response. Note the sharp cut-off at 5 Hz such that even though the spectrum is flat below 5 Hz there will be little aliasing at 4 or even 4.5 Hz.

Seismograms (3 and 4) and (5 and 6) were selected from Kazakh test sites. Signal 7 was intended to be from Azgir, but due to a mistake no signal is in the data window. The remaining signals are selected for good S/N from a few day's bulletins.

The signals are mostly teleseismic the exceptions, for which there are good signals, being signals 1,27,29,30, and 31. The last four are, unfortunately, all from one source region, Yugoslavia. Because the other signals are teleseismic and since they had to have large S/N in order to be suitably buried in the noise, they will have lower frequencies than regional events and generally lower frequencies than the teleseismic events of interest for detection. However, corner frequencies scatter greatly as a function of magnitude so that although the sample is probably biased many small teleseismic events would have these spectral shapes.

TELEDYNE
GEOTECH
ALEXANDRIA LABORATORIES

The signal windows are two minutes long and the P starts were centered in the window. Thus, there is 1 minute of noise in front. (Signals 2, 4, and 6, being Lg, the maximum of the vertical component was centered.) The signal windows were tapered with a 25% cosine taper to avoid abrupt starts and stops, then added to the noise. Each signal was added to the noise four times, first with the maximum equal to 1/2 the raw amplitude maximum in the 10 minute window, and then, at 1/4, 1/8, and 1/16 the amplitude. Thus, with the 34 signals in Table I there are a total of 4X34=136 10-minute (6000 points) windows. In each window a signal begins at the 9th minute (point 5400). The data are continuous from window to window.

Due to an error which occurred during the signal and noise merging there is a graded decrease of 50% in the rms noise in the 30 seconds preceding the 1/2 amplitude signals. With an LTA of ~ 30 seconds or less this makes these signals easier to detect than they should be. However, in general, the first window signals are easy to detect by analyst or macine and would be detected without this decrease so that I do not think this error will bias the use of the tape.

To provide a benchmark we have run a standard (optimum frequency filter, square, LTA ~ 30 seconds, STA ~ 1.5 seconds, detect in 3/3 successive windows) detector on the tape. The optimum S/N^2 filter is determined from the first 512 points of each 10 minute window, assuming a flat source spectrum and a $t^* = 0.3$. The resulting filter was nearly constant from window to window and fairly close to a 2-4 Hz 3rd order band-pass filter. Had we used a bandpass filter then the detector would have been equivalent to the standard IBM detector except that we squared instead of taking absolute values. Processing was 10 times real time on the 360/44 - most of the time was taken up in FFT's.

A detection was considered valid if it occurred in the 30 second time interval from 9 minutes to 9 minutes 30 seconds. At the false alarm rate (FAR) of one every (136x10)/161=8.4 minutes (see Table II), we expect 2.0 false alarms in each S/N gain level (2.0=(0.5x34)/8.4). Thus, this detector can be seen to be operating at approximately the 80% or better, 50%, 5% and 0% detection capability at the four gain levels. In general terms, other experiments using absolute values, longer STA windows, and t^* values ranging from 0 to 0.45 yielded results differing only slightly in detection.

A significant improvement would, for example, be detection of several signals at the next level below the lowest detected level for each signal. That is, detection of say, 5 of the underlined signals in Table II without increasing the FAR while continuing to detect the higher levels would be a significant improvement.

In general terms whenever the automatic detector triggered the signals could be detected visually by me when the raw data was plotted at a scale of 1" to 5 seconds. When the automatic detector could not detect the signal, neither could I. It might be that a more extended plot scale and a more experienced analyst might detect to lower levels; however, this is about the characteristic performance of the SDAC operational 11/70 detector.

Table I

NORSAR SIGNAL LIST

Serial Order	Seis. No.	Original Sample Rate	Date	Arrival Time ~ 1-min	Lat	Long.	NAO m_b	Δ°
1	1	20.0	04 Sep 72	07 01 47.0	67N	33E	5.0	11.9
2	2	20.0	04 Sep 72	07 04 59.0	Lg			
3	3	10.0	18 Dec 78	08 04 20.0	48N	48E	6.3	W. Kazakh
4	4	10.0	18 Dec 78	08 12 17.0	Lg			
5	5	10.0	31 May 79	06 01 17.0	49N	78E	5.3	E. Kazakh
6	6	10.0	31 May 79	06 14 29.0	Lg			
7	7	10.0	10 Jun 79	08 04 17.0	No signal			
8	8	10.0	10 Sep 78	12 55 08.0	39N	140E	5.2	68
9	9	10.0	11 Sep 78	07 51 55.0	27N	129E	5.5	81
10	10	10.0	12 Sep 78	00 52 27.0	30N	132E	5.7	77
11	11	10.0	13 Sep 78	04 39 27.0	18N	146E	5.7	84
12	12	10.0	15 Sep 78	11 49 14.0	49N	156E	5.5	67
13	13	10.0	16 Sep 78	23 56 17.0	24S	176W	5.3	144
14	14	10.0	21 Sep 78	15 05 21.0	68N	87E	5.3	32
15	15	10.0	23 Sep 78	22 53 40.0	39N	140E	5.4	74
16	16	10.0	23 Sep 78	16 49 56.0	8S	157W	6.5	130
17	17	10.0	09 Apr 79	13 12 00.0	52N	160E	4.8	61
18	18	10.0	10 Apr 79	01 55 01.0	6N	128E	6.6	100
19	19	10.0	01 Apr 79	04 33 52.0	64N	18W	4.2*	14
20	20	10.0	01 Apr 79	13 25 39.0	11N	125E	5.3	95
21	21	10.0	01 Apr 79	22 14 41.0	52N	160E	4.7	65
22	22	10.0	02 Apr 79	03 57 36.0	19N	102W	4.9	85
23	23	10.0	02 Apr 79	17 36 57.0	39N	140E	5.1	73
24	24	10.0	03 Apr 79	17 44 21.0	25S	180W	4.6	142
25	25	10.0	04 Apr 79	13 31 26.0	16N	121E	5.6	83
26	26	10.0	06 Apr 79	23 57 15.0	44N	150E	5.2	70
27	27	10.0	15 Apr 79	14 46 34.0	42N	19E	4.4	20
28	28	10.0	15 Apr 79	18 28 02.0	34S	180E	4.3*	48
29	29	10.0	19 Apr 79	00 21 05.0	42N	19E	3.8	19
30	30	10.0	19 Apr 79	05 46 22.0	42N	19E	3.3	20
31	31	10.0	22 Apr 79	06 35 44.0	42N	19E	3.6	20
[illegible]	32	10.0	22 Apr 79	09 58 14.0	41N	30W	5.5	43
33	33	10.0	24 Apr 79	02 02 21.0	24S	176W	5.9	139
[illegible]	34	10.0	24 Apr 79	08 16 07.0	41N	142E	5.2	70

* NEP m_b

Table II

Raw S/N	1/2 FA	1/2 D	1/4 FA	1/4 D	1/8 FA	1/8 D	1/16 FA	1/16 D	Comments *
1	3	1	1	1	2	1	2	0	High frequency, 5 sec
2	2	1	1	1	1	1	1	0	Lg 1-4 Hz, 30 sec
3	2	1	1	1	1	1	1	0	Clipped, therefore a <u>very</u> high frequency "event, 30 sec
4	2	1	1	0	2	0	2	0	Lg long STA would work well, 30 sec
5	0	1	1	1	1	0	2	0	2.5-3.5 Hz, 2 sec
6	2	0	0	0	2	0	3	0	Lg possibly very low frequency
7	3	0	1	0	2	0	2	0	*No signal due to some mistake*
8	4	1	2	1	1	0	1	0	2-4 Hz, 3 sec
9	1	1	1	0	0	0	0	0	1-3 Hz, 5-10 sec
10	2	1	0	0	1	0	0	0	1-2 Hz, 2-10 sec
11	1	1	2	1	0	0	0	0	2-3 Hz, 2-5 sec
12	1	1	2	0	0	0	3	0	1.5-2.5 Hz, 3 sec
13	3	1	2	0	1	0	3	0	Nothing visible, 2 sec
14	2	1	1	1	1	0	0	0	1.5 Hz, 3 sec
15	3	1	2	0	2	0	2	0	1 Hz, 3 sec
16	1	1	1	1	2	0	0	0	1-2 Hz, 5 sec
17	0	1	1	0	1	0	2	0	Very short signal, 2 sec
18	0	1	1	0	1	0	0	0	1-2.5, 2 sec
19	0	0	1	0	2	0	3	0	2 Hz - 30 sec
20	1	0	3	1?	1	0	1	1?	No visible signal, 3 sec
21	1	1	0	1	0	0	2	0	1-3 Hz, 3-10 sec
22	2	1	0	0	0	1?	1	0	No visible signal, too weak
23	0	1	2	1	1	0	0	0	1-4.5 Hz, 10-30 sec
24	0	1	0	0	0	0	0	1?	1 Hz, 20 sec
25	0	1	0	0	2	0	3	0	2 Hz, 2 sec
26	0	1	0	1	2	0	0	0	3 Hz, 2 sec with precursor
27	2	1	0	0	.3	0	1	0	1-4 Hz, 20 sec
28	1	0	1	0	2	0	0	0	No visible signal, 3-10 sec
29	1	1	2	1	4	0	2	0	1-4 Hz, 20 sec
30	1	1	1	1	2	0	1	0	1-4 Hz, 5 sec
31	1	1	0	0	2	0	1	0	3-4 Hz, 10 sec
32	1	0	1	0	1	0	2	0	No visible signal, nothing
33	0	1	0	1	0	0	0	0	1-3 Hz, 5 sec
34	0	1	3	1	2	0	1	0	1-5 Hz, 5 sec
D	43/23		35/16		45/4		41/2		

Total FA = 164

Expected number of false detections/gain level = 2.0

~ 80% ~ 50% ~ 5% ~ 0%

* Comments before first comma are obtained by inspection of the S/N= 1/2 traces, comments after first comma are obtained by inspection of original signals. Comments after comma were not in original memo of 6 June.

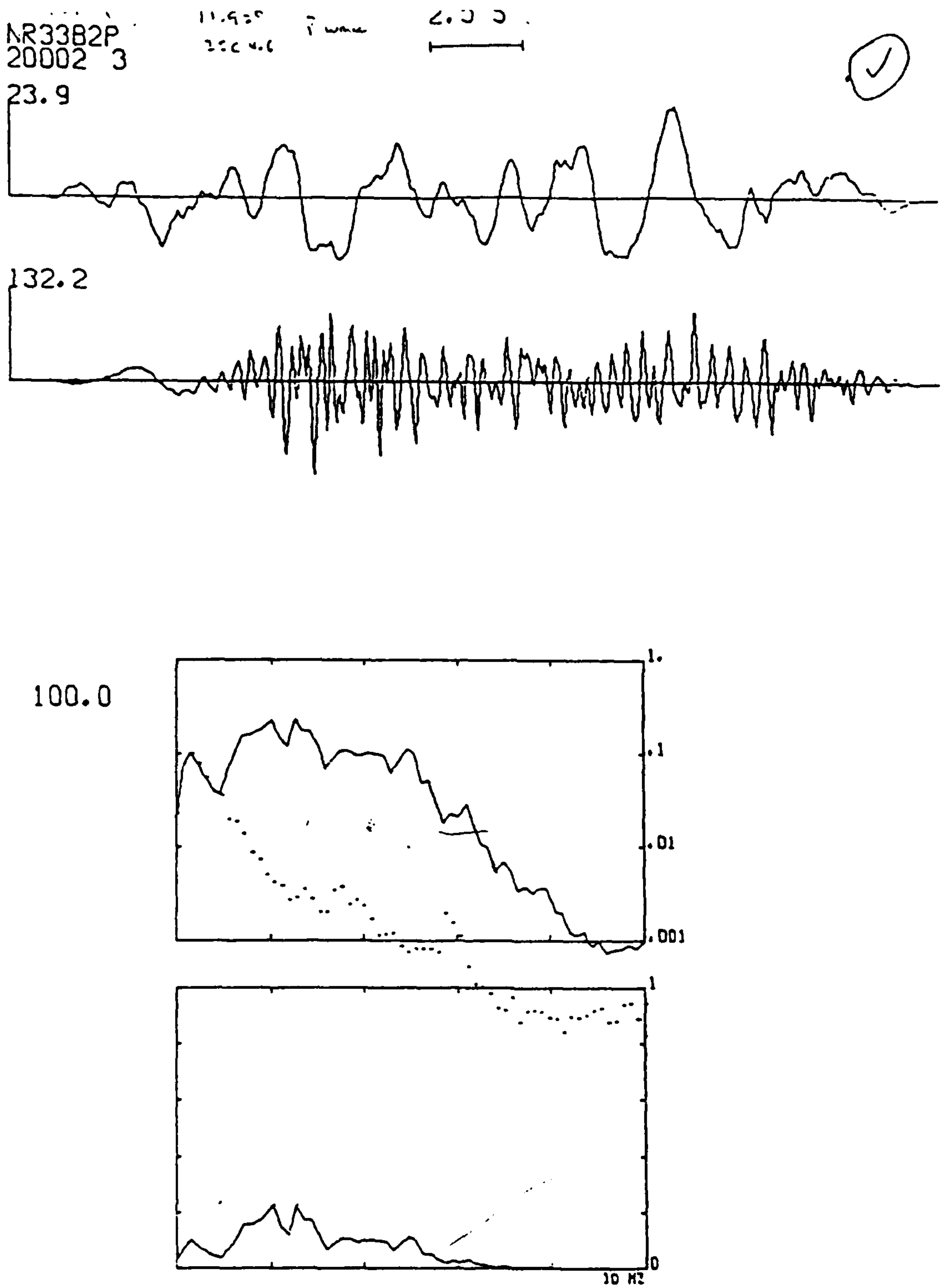


Figure 1

APPENDIX III

JULY 2, 1980 GEOTECH MEMORANDUM FROM R. R. BLANDFORD,
"TAPE CONSTRUCTION AND BENCHMARK DETECTION RESULTS FOR PINEDALE"

MEMORANDUM

TELEDYNE GEOTECH

ALEXANDRIA LABORATORIES

TO: Recipients of the 3 July 1980 VSC Detection Experiment Tape

FROM: R. R. Blandford

DATE: 2 July 1980

SUBJECT: Tape Construction and Benchmark Detection Results

The noise data are from March 7 and 8, 1980, as transmitted by phone line at 20 sps from Pinedale Wyoming. This period was selected to minimize signals, data dropouts and system down time. The data are from the single vertical KS 36000 instrument, (channel 9). A FORTRAN computer program was written to create "artificial" noise which would have no signals in it. The program operated in the identical manner as that discussed in my June 6, 1980 memorandum about the 30 May VSC 10 sps NORSAR detection tape.

Table I gives the list of event arrival times, distance, latitude and longitude and magnitudes. It can be seen that except for events 7, 8, 30 and 31 the data are teleseismic and of large magnitude. In general, the dominant periods are 1 second or longer--much longer periods than at NORSAR. Signal envelope lengths range from 3 to 50 seconds.

The signal windows are two minutes long and the P starts were centered in the window. Thus, there is one minute of noise in front. The signal windows were tapered with a 25% cosine taper to avoid abrupt starts and stops, then added to the noise. Each signal was added to the noise four times, first with the maximum equal to 1/2 the raw amplitude maximum in the 10 minute window, and then, at 1/4, 1/8 and 1/16 the amplitude. Thus, with the 31 signals in Table I, there are a total of 4 x 31 = 124 10-minute (12000 points) windows. In each window a signal begins at the 9th minute (point 10800). The data are continuous from window to window.

To provide a benchmark we have run a standard (decimate to 10 sps, optimum frequency filter, square, LTA 30 seconds, STA 1.8 seconds, detect in 3/3 successive windows) detector on the tape. The optimum S/N^2 filter is determined from the first 512 points of the decimated data for each 10 minute window, assuming a flat source spectrum and a $t^* = 0.3$. Remaining remarks are similar to those in my June 6 memo.

In Table II we see the results.

PWY SIGNAL LIST

Sig. Order	Seis. No.	Sample Rate	Date	Arrival Time —1 min	Lat.	Long.	Δ	m_b	
1	1	20.0	12 Sep 78	00:53:35.0	29.8N	129.5E	89.6°	5.3	
2	2	20.0	13 Sep 78	04:39:31.0	26.4N	142.0E	84.8°	5.0	
3	3	20.0	15 Sep 78	11:48:50.0	48.2N	154.3E	63.2°	6.1	
4	4	20.0	16 Sep 78	23:49:57.0	25.8S	177.9W	92.8°	5.1	
5	5	20.0	25 Sep 78	02:12:42.0	41.3N	125.5W	11.9°	4.8	
6	6	20.0	25 Sep 78	21:48:13.0	50.9N	156.2E	60.7°	4.6	
7	7	20.0	24 Jan 79	18:00:51.0	37.1N	116.W	7.5°	4.5	
8	8	20.0	23 Mar 79	17:24:41.0	26.7N	110.8W	15°	5.1	
9	9	20.0	09 Apr 79	02:03:40.0	10.5N	82.6W	39.8°	4.9	
10	10	20.0	12 Apr 79	00:25:03.0	17.8S	178.2W	87.2°	5.0	
11	11	20.0	14 Apr 79	02:51:34.0	35.0S	106.8W	77.5	5.5	
12	12	20.0	14 Apr 79	10:11:27.0	35.7S	102.5W	78.4°	5.6	(7 sec earlier a 4.6 m_b same loc)
13	13	20.0	15 Apr 79	06:31:15.0	41.9N	19.1E	83.8°	6.0	
14	14	20.0	15 Apr 79	13:39:06.0	3.4N	82.9W	45.8°	5.0	
15	15	20.0	15 Apr 79	14:54:34.0	42.1N	18.7E	83.5°	5.4	
16	16	20.0	16 Apr 79	10:16:09.0	41.9N	19.4E	84.0°	5.0	
17	17	20.0	16 Apr 79	21:03:46.0	51.2N	179.3W	46.6°	4.4	
18	18	20.0	18 Apr 79	13:27:49.0	51.4N	170.6W	41.4°	4.6	
19	19	20.0	18 Apr 79	18:09:44.0	24.4S	67.2W	77.4°	5.2	
20	20	20.0	18 Apr 79	22:15:38.0	32.4N	41.2W	53.8°	5.1	
21	21	20.0	21 Apr 79	13:29:49.0	52.3N	169.6W	40.6°	4.5	
22	22	20.0	22 Apr 79	09:58:42.0	32.9N	39.6W	54.6°	5.4	
23	23	20.0	26 Apr 79	02:11:35.0	33.9S	71.9W	83.7°	5.4	
24	24	20.0	28 Apr 79	01:05:41.0	18.2S	174.8W	85.2°	5.2	
25	25	20.0	28 Apr 79	11:49:18.0	27.5S	71.0W	78.4°	5.5	
26	26	20.0	29 Apr 79	14:07:35.0	15.2S	178.5W	85.5°	5.4	
27	27	20.0	29 Apr 79	16:10:24.0	22.5S	177.4W	90.1°	5.4	
28	18	20.0	05 May 79	20:12:38.0	8.4N	71.0W	48.1°	5.5	
29	29	20.0	05 May 79	20:16:18.0	8.7N	71.1W	47.8°	5.3	
30	30	20.0	06 Aug 79	17:06:59.0	37.1N	121.5W	10.5°	5.4	
31	31	20.0	15 Oct 79	23:18:37.0	32.6N	115.3W	11.0°	5.7	

TABLE I

Window		Signal	1/2 F	1/2 D	1/4 F	1/4 D	1/8 F	1/8 D	1/16 F	1/16 D	Comments
1	4	1	2	1	1	0	2	0	1	0	4 sec
5	8	2	0	1	1	1	1	0	0	0	3 sec
9	12	3	0	1	1	1	0	1	0	0	3 sec clipped
13	16	4	1	1	3	0	2	0	0	0	3 sec
17	20	5	2	0	1	0	1	0	0	0	10 sec, LF*
21	24	6	0	1	1	1	2	0	0	0	3 sec
25	28	7	0	1	2	1	0	0	2	0	30 sec HF
29	32	8	0	1	3	0	1	0	2	0	40 sec LF
33	36	9	0	1	0	0	2	0	1	1	3 sec
37	40	10	0	1	2	1	2	0	0	1	3 sec
41	44	11	0	1	0	1	0	0	2	0	30 sec
45	48	12	0	1	3	0	1	0	3	0	20 sec, v. emergent
49	52	13	0	1	0	1	3	1	1	0	30 sec, clipped
53	56	14	1	0	1	0	0	0	0	0	3 sec
57	60	15	1	1	0	0	1	0	0	0	10 sec LF
61	64	16	1	1	1	1	5	0	0	0	10 sec
65	68	17	0	1	0	1	2	0	0	0	3 sec HF
69	72	18	1	1	0	0	2	0	0	0	3 sec
73	76	19	0	1	0	0	1	0	1	0	10 sec, spikes @ 25 sec in noise
77	80	20	1	1	1	0	3	0	0	0	3 sec
81	84	21	3	1	0	1	1	1	0	0	3-20 sec
85	88	22	0	1	1	1	0	0	0	0	20 sec
89	92	23	0	1	0	1	1	0	2	0	40 sec
93	96	24	0	1	0	0	1	0	1	0	5-10 sec VLF
97	100	25	1	1	2	0	2	0	1	0	10 sec, 10 sec late
101	104	26	0	0	0	0	1	0	2	0	25 sec
105	108	27	0	1	0	0	2	0	1	0	3 sec
109	112	28	1	1	0	0	1	0	1	0	12 sec
113	116	29	1	1	1	0	0	0	1	0	3 sec
117	120	30	0	1	1	1	2	0	4	0	~ 60 sec
121	124	31	0	1	1	1	1	0	3	0	~ sec
			17	28	27	14	43	3	29	2	

* LF - low frequency, HF - high frequency

TABLE II. False alarms (F) and detections (D) for Pinedale signals at four levels of S/N. Detector runs on decimated data (10 sps), optimum S/N^2 filter, squared, STA = 1.8 sec, LTA = 30 sec, 3/3 successive detections. False alarm rate 1/10.7 min. Expected false detections per S/N level is ~ 1.4.

APPENDIX IV

DESCRIPTION OF THE SRC (SDAC) ON-LINE DETECTION SYSTEM

TABLE OF CONTENTS

INTRODUCTION

In general terms the on-line detection system as of this writing (January 1981) represents a translation to FORTRAN of the detection algorithm programmed by IBM workers in microcode and machine language. For the theory of this detector see Vanderkulk et al (1965), and for the earlier detailed description of the code perhaps the most accessible reference is the SDAC DP Systems reference, several copies of which are available at the SDAC in Alexandria. For all except the most determined history of science workers, however, this appendix should be the reference of choice for programming considerations. The present on-line program has features not available in the older on-line system such as diagnosis of drop-outs, complex spikes, and regionals. The regionals are diagnosed using the spectral ratio proposed by von Seggern (1977). Another new feature is the automatic refinement of start times. Because the original IBM system also beamformed arrays it had a feature not in the present system, i.e., after detections the array of beams would be scanned in space and time to find the beam with the largest STA/LTA and for which it or its neighbor had been the largest k consecutive times. That beam would be the detection beam.

When the IBM system was reprogrammed in machine language to handle multiple arrays a mistake was apparently made, resulting in inconsistent detection performance. To remedy this problem, the system was reprogrammed in FORTRAN to run under UNIX on the PDP 11/70 at the SDAC. To provide as much continuity as possible, the program was made functionally as identical to the IBM system as possible.

Because of the use of microcode it was possible to use only one filter in the IBM system. Our on-line system uses a filter designed according to S/N^2 principles for station BFAK. It is a 1.2-3 Hz bandpass. As we have seen elsewhere in this report, this is not optimum for the on-line PWY channel.

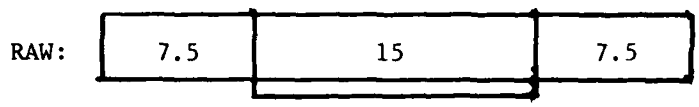
As a result of the work discussed elsewhere in this report, the on-line system will soon be changed to allow different filters, to square the data, to detect on only a single threshold crossing, and perhaps to use the Z-log transform and perhaps to use a 10-second window for detection. Other work is also underway on incoherent detection.

QUALITATIVE DISCUSSION OF THE DETECTION SUBROUTINE (STALTA)

Subroutine STALTA contains the detection algorithm. Inputs to STALTA are:

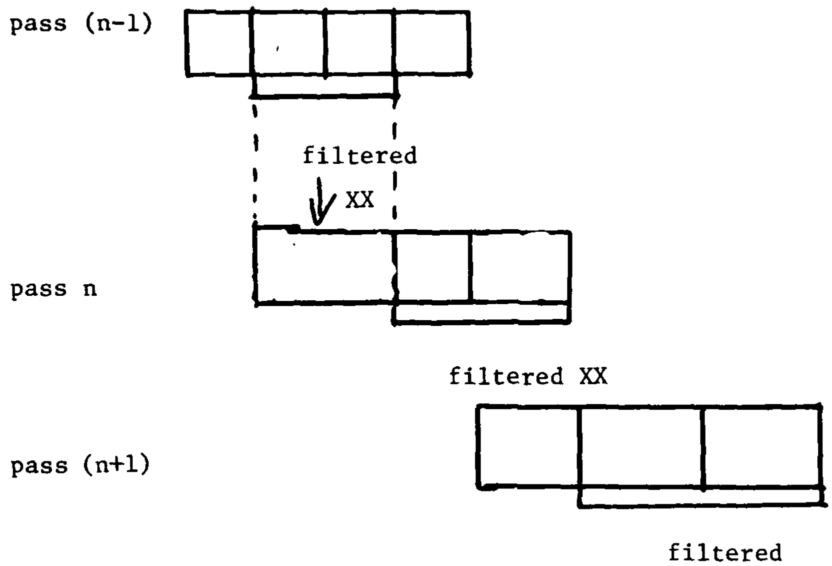
CHANID	-	a 14-character string identifying the current channel
RAW	-	a floating point array containing the demultiplexed and degained data for the current channel and time window.
ICHAN	-	an integer array containing parameters for the current channel
CHAN	-	a real array equivalenced to ICHAN
XX	-	real array storing previously filtered data used to eliminate transient ringing in the recursive filter
STA	-	integer array containing current set of short term averages
Y	-	integer array containing intermediate averages
LTA	-	integer value of current Long Term Average
QR	-	integer array containing "detections" for 'Q out of Q' criterion
DETN	-	logical flag indicating "detection in progress"
DISP	-	logical flag indicating waveform output should be produced
DSTA,DLTA	-	floating point representations of "instantaneous" STA and LTA
DTIME	-	floating point start time of detection
STATUS	-	character description of detection - 'drop-out', 'local', etc.

1) Given input data array of 30 seconds worth of data structured as:



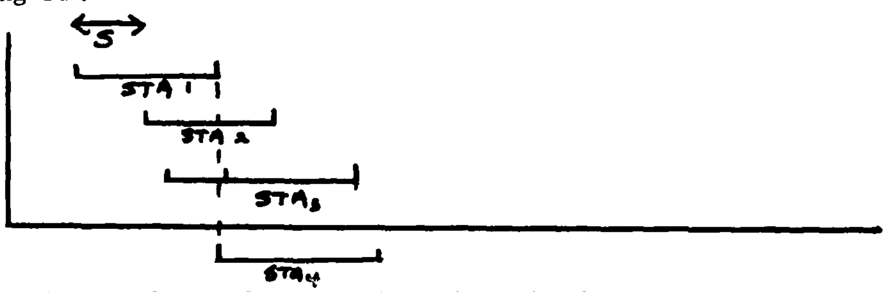
(1.2-3 Hz, 6-pole Butterworth)

recursively filter segments 2 and 3 onto a new array called FILTER. Segment 3 is saved to be used as segment 1 of the next pass. Thus



2) Turn on and turn off threshold are defined.

3) Begin moving average over points taken "S" at a time. This corresponds to sliding STA



The LTA is updated whenever the STA window has moved into a completely new set of points. Thus, after STA 4 was computed, the LTA would be updated using the data from STA.

The absolute value of the data is used i.e.,

$$STA_i = \sum_{i=1}^{S} \left| filter(i) \right|$$

This is for continuity with earlier detector, squaring is optimum.

4) The STA/LTA threshold is compared against the current threshold. If it exceeds that threshold, a flag is set.

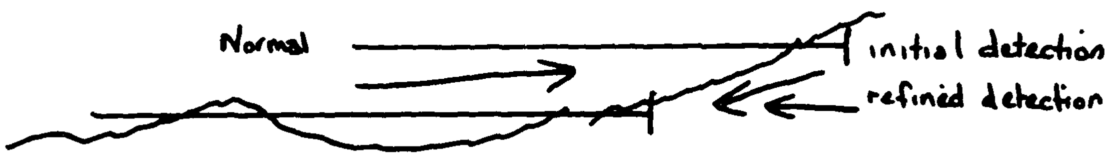
5) If STA/LTA exceeds the threshold for Q/Q' time segments (for on-line DP this amounts to 3 successive exceedings), we may declare a detection.

6) $\left\{ \right.$See decision matrix for full definition of start. Optimum Q/Q' is 1/X, any x. 3/3 is used for continuity.$\left. \right\}$

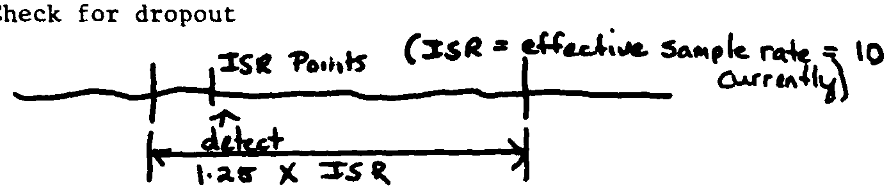
Given we have a detection start:

a) Compute the maximum STA of the three used in declaring the event - save this to be output as the amplitude.

b) Refine the start time by lowering the threshold and back up



c) Check for dropout



we check the RAW (not filtered) data for ISR/2 consecutive zeros. If these are found, we assume a data gap and bypass further processing. A search window beginning earlier is desirable to check for data re-acquisition. A large number of consecutive zeros are needed for under-quantized data as is characteristic of ALK. For NORSAR two zeros in a row would be diagnostic.

d) Check for type 1 spikes ← see spkchk

e) FFT computation = mean removal, 10% split cosine bell taper. Inverse X form after removing low frequency components

f) Check for spikes on filtered data

g) Compute periodogram. Take spectral ratio of low frequency to high frequency. Categorize as "local" or "teleseismic" via spectral ratio

End of Detection Start processing.

If Detection End - i.e., 3 consecutive STA's less than end threshold. We report everything regarding this detection.

LTA is updated every R STA's.

LTA update is skipped if the detection was a dropout or spike.

Two different LTA decay constants are used depending on whether a detection is in progress or not. This is to close down a detection rapidly so that later phases will be detected.

The start and end threshold are updated to reflect the new LTA .

Recursive Filter Algorithm

$$F(n\Delta t) = \sum_{p=0}^{\underline{P}-1} a_p \cdot f((n-p)\Delta t) + \sum_{p=1}^{\underline{P}-1} b_p \cdot F((n-p)\Delta t))$$

Letting $\Delta t \equiv$ unity yields the formally simpler expression

$$F(n) = \sum_{i=0}^{\underline{P}-1} a_i \cdot f(n-i) + \sum_{i=1}^{\underline{P}-1} b_i \cdot F(n-i)$$

where f represents the raw data

F reprsents the filtered data

$\underline{P}$ represents the degree of filter.

Detection Algorithm

A) Intermediate STA — in our case S = 3 for all channels

$$y(n) = \sum_{i=0}^{S-1} |F(n - c|$$

B) Short Term Average

$$STA(n) = STA(n-1) - y\ (n-R) + y(n)$$

R = 3

c) Long Term Average

$$LTA(n) = e^{-\sigma} STA(n) + (1 - e^{-\sigma})\ LTA(n-1)$$

STA >TH	DETN	Q/Q'	No Arrival	Start	Continue	End
N	N	N	X			
N	N	Y	-	-	-	-
N	Y	N				X
N	Y	Y			X	
Y	N	N	X			
Y	N	Y		X		
Y	Y	N	-	-	-	-
Y	Y	Y			X	

In the current detector Q/Q' is 3/3.

Frequency Domain Spike Check

Not to be confused with deglitch algorithm which is designed to eliminate "single point" glitches.

$$\left[\begin{array}{l} \text{Deglitch} \rightarrow \text{ if } |f(i-1)| < G, \text{ and } |f(i)| > 10G, \text{ and } |f(i+1)| < G \\ \qquad f(i) \leftarrow f(i-1) \\ \qquad \text{Normally } G = 20.0 \end{array}\right]$$

Despike: A specific algorithm for complex ALK spikes.

Take window 6.4 sec - same as FFT window of 64 points at 10 Hz of data around possible detection

a) IF $|i_{max} - i_{min}| < 10$ AND $\left\{ \left|\frac{max}{min}\right| > 1.5 \text{ OR } \left|\frac{max}{min}\right| < 1/1.5 \right\}$

THEN define detection as TYPE-1 spike

b) Apply FFT to data; compute spectral ratio $R = \dfrac{\sum_{\omega f=2\ Hz}^{4\ Hz} F(\omega)}{\sum_{\omega=1\ Hz}^{2\ Hz} F(\omega)}$

c) Zero transform components < 0.3 Hz and
inverse transform to remove microseism trends so that small ALK spikes may be analyzed.

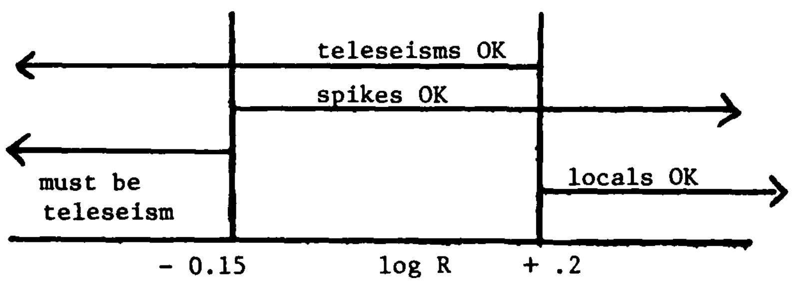
d) for new data window apply test of a) above but with 1.5 replaced by 2 to check for Type 2 spikes.

e) if not a spike

$\log R < .2$ "teleseism"

$\log R > .2$ "regional"

if "spike" but $\log R < -.15$ "teleseism".



Summary Graph

RIT

Feb 5 16:37 1981 rit.h Page 1

```
c
c...  Detection Criterion Common
c
c...  NPTS    - No. of DATA points to process
c...  S       - No. of DATA points to average for intermediate sta (Y)
c...  NS      - No. of Y's to average for STA
c...  R       - Interval in STA units between LTA update
c...  Q       - q  in q/q' criterion
c...  QP      - q' in q/q' criterion
c...  TRNON   - Turn-on  Threshold
c...  TRNOFF  - Turn-off Threshold
c...  TSUBC   - Normal LTA Decay Time constant
c...  TSUBCD  - Decay Time constant during detection
c
c...  IDX     - Coherency distance for Spkchk routine
c...  BRATIO  - 'Big Spike' ratio   "    "      "
c...  SRATIO  - 'Small Spike' ratio "    "      "
c
c...  IFLO    - Low FFT_channel for Spectral Ratio Calculation
c...  IFMID   - Middle   "     "     "     "      "
c...  IFHI    - High     "     "     "     "      "
c...  IFCUT   - Cutoff FFT_channel for inverse filtering
c...  SPECT   - Local/Teleseism Discrimination Ratio
c...  BCOEF   - B-coefficients for recursive filters
c
      Real TRNON, TRNOFF, TSUBC, TSUBCD
      Real BRATIO, SRATIO, SPECT, BCOEF(0:6,3)
      Integer*2 IDX, NPTS, R, Q
      Integer*2 IFLO,IFMID,IFHI, IFCUT
      Common /rit/ TRNON, TRNOFF, TSUBC, TSUBCD,
     &         BRATIO, SRATIO, SPECT, BCOEF,
     &         NPTS, R, Q, IDX, IFLO,IFMID,IFHI, IFCUT
c
c   End of rit.h
```

```
c
c...  Channel Parameters
      Parameter (Maxcha=7)
c
c...  NDET    - Number of channels to be proccessed
c...  LTA     - Current LTA value
c...  STA     - STA array; QP points
c...  QR      - Work area for q/q' calculation; QP+1 points
c
      Integer*2 NDET
      Real LTA(Maxcha), STA(5,Maxcha)
      Integer*2 QR(5,Maxcha)
c
c...  XX      - Filter save area; 75 points
c...  DETN    - Flag indicating 'detection in progress'
c...  DLTA    - LTA at start of detection
c...  DSTA    - STA at  "   "     "
c...  DTIME   - Time at "   "     "
c...  STATUS  - Alphanumeric detection type (Local, Spike_1, etc.)
c...  CHANID  - Alphanumeric channel id
c
      Real XX(75,Maxcha)
      Logical DETN(Maxcha)
      Real DETECT(6,Maxcha)
      Character*10 STATUS(Maxcha)
      Character*14 CHANID(Maxcha)
c
c
c...  ICHAN contents:
c
c...   1) Integer     - Site number
c...   2) Integer     - Displacement to channel in DPS record
c...   3) Integer     -      "       "    "   in site
c...   4) Integer     - Increment to next point in site
c...   5) Real        - Calibration in nm/count for RAW data
c...   6) Real        - Delay of site data relative to DPS Tape TOD
c...   7) Integer     - Seconds of Data Processed
c...   8) Integer     - Number of Local    Detections
c...   9) Integer     -   "    "  Teleseismic  "
c...  10) Integer     -   "    "  Spike_1      "
c...  11) Integer     -   "    "  Spike_2      "
c...  12) Integer     -   "    "  gram files produced
c
      Integer*4 ICHAN(12,Maxcha)
      Real*4 CHAN(12,Maxcha)
      Equivalence (ICHAN(1,1), CHAN(1,1))
c
c...  Storage for Demultiplexed data
c...  Note that the last 150 elements of RAW1 are not used in the
c...  demux operation and are free for other uses.
c
      Real RAW0(150)
      Real RAW1(300,Maxcha)
      Real RAW2(300,Maxcha)
      Equivalence (RAW1(1,1),RAW2(151,1))
      Equivalence (RAW0(1), CHAN(1,1))
```

```
c
       Common /sites/ RAW2,RAW0, XX,DETECT,
      &         NDET,LTA,STA,QR, CHANID, STATUS, DETN
c
c   End of sites.h
```

```
      Subroutine Stalta (CHANID, RAW, ICHAN, CHAN, XX,STA,
     &          LTA, QR, DETN,DETECT,STATUS)
      Parameter (ISR = 10)
      Parameter (S = 5, NS = 3, QP = 3)
c
c...  STALTA computes the short & long term averages of the
c...  filtered input.  The ratio of STA/LTA is compared to
c...  a threshold value to define a detection.
c
      Include 'rit.h'
      Include 'run.h'
c
      Character*14 CHANID
      Integer*4 ICHAN(*)
      Real*4 CHAN(*)
      Real RAW(*), XX(*), STA(*), LTA
      Integer*2 QR(*)
      Logical DETN
      Real DETECT(6)
      Character STATUS*10
c
      Real calib, delay
      Complex xc1(64), xc2(64)
      Real dt, df, dtlta, dtsta, fltlta
      Real qsum, sumlo, sumhi, fmax
      Real e2sig, sigf, e2sigd, sigdf
      Real statim, rawtim,filtim
      Real xr1(64), xr2(64)
      Real filteq(300), filter(150)
      Equivalence (filter(1),filteq(76))
      Real tsrt,tend,th, cursta
      Integer*2 i,j, i1,i2
      Integer*2 iknt, nsta
      Integer*2 detptr,filptr,rawptr,fftptr
      Logical big, qqp, first
      Logical detsrt, detend, saqout
      Logical drop, BSPK, SSPK,valid
c
      Data first/.true./
      Data filteq /300*0.0/
c
c...  Initial Setup Section
c...  Done only if LTA = -999.9
c
      If (LTA.eq.-999.9) Then
c
c...  Define scaling factors
c
          dt = 1.0/Float(ISR)
          df = 1.0/(64*dt)
          dtsta = S*dt
          dtlta = (R*S)*dt
          e2sig = 1.0 - Exp(-dtlta/tsubc)
          sigf = 1.0 - e2sig
          e2sigd = 1.0 - Exp(-dtlta/tsubcd)
          sigdf = 1.0 - e2sigd
```

```
c
c...  Compute initial LTA and thresholds
c
         Call Rfil (NPTS,BCOEF(0,ICHAN(12)),RAW(151),filter)
         LTA = 0
         Do 20 i = 1,S*NS
   20       LTA = LTA+Abs(filter(i))
         If (first) Then
            first = .false.
            Call Header
         Endif
         saqout = .false.
         statim = timei+dtsta
         fltlta = Float(LTA)/(S*NS)
         DETECT(4) = 0.0
         DETECT(5) = 0.0
         Call Report (CHANID,statim,'Initial   ',0.0,fltlta,
     &                statim,saqout,DETECT(4))
      Endif
c
c...  Get channel calibration and delay
c
      calib = chan(5)
      delay = chan(6)
c
c...  Load up previous filtered data to avoid start-up ring
c...  Filter the data to be used in the STA/LTA calculation
c
      Do 40 i = 1,75
   40    filteq(i) = XX(i)
      Call Rfil (NPTS,BCOEF(0,ICHAN(12)),RAW(76),filter)
      Do 42 i = 1,75
   42    XX(i) = filteq(i+150)
c
c...  Set up display times and files
c...  Filter time delay is 0.3 sec for Rfil
c
      rawtim = timei-15.0+delay
      filtim = timei-15.0+delay-0.3
      statim = timei- 7.5+delay-0.3-dtsta
c
c...  Define thresholds
c
      tsrt = TRNON*LTA
      tend = TRNOFF*LTA
      th = tsrt
      If (DETN) th = tend
c
c...  Set up STA & LTA Storage
c...  Begin Loop over data
c
      nsta = 1
      Do 1000 filptr = 1,NPTS,S
      cursta = 0.0
      i1 = filptr-(S*(NS-1))
      i2 = filptr+(S-1)
```

```
      Do 100 i = i1,i2
  100    cursta = cursta+Abs(filter(i))
      nsta = nsta+1
      statim = statim + dtsta
c
c...  Shift detection flag array;
c...  Check for STA/LTA > threshold;
c
      Do 110 i = 1,QP-1
         STA(i) = STA(i+1)
  110    QR(i) = QR(i+1)
      STA(QP) = cursta
      big = .false.
      QR(QP) = 0
      If (cursta.ge.th) Then
         big = .true.
         QR(QP) = 1
      Endif
      qsum = 0
      Do 112 i = 1,QP
  112    qsum = qsum+QR(i)
      qqp = .false.
      If (qsum.ge.Q) qqp = .true.
c
c...  Check for detection:
c...  big = true if last STA > threshold
c...  qqp = true if q/q' STA's > threshold
c...  DETN = true if a detection is in progress
c
      detsrt = .false.
      detend = .false.
c
c...  Detection Start?
c
      If (big .and. .not.DETN .and. qqp) Then
         detsrt = .true.
         valid = .true.
         DETN = .true.
         th = tend
         rawptr = filptr+75
         Call Refine (filteq,rawptr, STA(QP-1), LTA, detptr)
         DETECT(1) =  filtim + (detptr-1)*dt
         DETECT(2) = 0.0
         Do 120 i = 1,QP
              If (STA(i).gt.DETECT(2)) DETECT(2) = STA(i)
  120    Continue
         DETECT(2) = DETECT(2)/Float(S*NS)
         DETECT(3) =  LTA/Float(R*S)
c
c...  Check for detection on data drop-out.
c
         iknt = 0
         drop = .false.
         Do 125 i = (detptr-(ISR/4)),detptr+ISR
              If (RAW(i).ne.0) Then
                 iknt = 0
```

```
              Else
                 iknt = iknt+1
              Endif
              If (iknt.ge.ISR/2) drop = .true.
 125      Continue
          If (drop) Then
              STATUS = 'Drop-out'
              DETECT(4) = -999.99
              valid = .false.
              Goto 150
          Endif
c
c...  Load up FFT buffer
c
          fftptr = detptr-(64/2)
          Do 130 i = 1,64
              j = fftptr+(i-1)
              xrl(i) = RAW(j)
 130      Continue
c
c...  Check for Big spikes
c
          Call Spkchk (64, xrl, IDX, BRATIO, BSPK)
          If (BSPK) Then
              STATUS = 'Spike_1'
              ichan(10) = ichan(10)+1
              valid = .false.
          Endif
c
c...  Detrend & taper the data
c
          Call Detrnd (xrl,64,0)
          Call Taper  (xrl,64,0.1)
c
c...  Load up complex array & do FFT
c
          Do 132 i = 1,64
 132          xcl(i) = Cmplx(xrl(i),0.0)
          Call Nlogn (6,xcl,-1.0)
c
c...  Load up inverse transform buffer
c...  Remove low frequency components from FFT data;
c...  Do inverse transform
c
          Do 134 i = 1, 64
 134          xc2(i) = xcl(i)
c
          xc2(1) = (0.0,0.0)
          Do 140 i = 2,IFCUT
              xc2(i) = (0.0,0.0)
              xc2(64-(i-2)) = (0.0,0.0)
 140      Continue
          Call Nlogn (6,xc2,+1.0)
c
c...  Pull out inverse xformed data
c
```

```
          Do 142 i = 1,64
  142          xr2(i) = Real(xc2(i))
c
c...  Check for Small spike
c
          If (.not.BSPK) Then
               Call Spkchk (64,xr2,1024,SRATIO, SSPK)
               If (SSPK) Then
                  STATUS = 'Spike_2'
                  ichan(11) = ichan(11)+1
                  valid = .false.
               Endif
          Endif
c
c...  Compute the amplitude spectra.
c
          DETECT(5) = 0.0
          fmax = 0.0
          Do 144 i = 1,33
               xr1(i) = Sqrt(Real(xc1(i))**2 + Aimag(xc1(i))**2)
               If (xr1(i).ge.fmax) Then
                  fmax = xr1(i)
                  DETECT(5) = Float(i-1)*df
               Endif
  144     Continue
c
c...  Compute the spectral ratio
c
          sumlo = 0.0
          Do 146 i = IFLO,IFMID
  146          sumlo = sumlo+xr1(i)
          sumhi = 0.0
          Do 148 i = IFMID+1,IFHI
  148          sumhi = sumhi+xr1(i)
c
c...  If valid detection, use Spectral Ratio for Local/Teleseismic
c...  discrimination.  ALL detections with logSR < -0.15 are called
c...  teleseisms.
c
          DETECT(4) = -999.99
          If (sumlo.gt.0.0 .and. sumhi.gt.0.0)
     &           DETECT(4) = Log10(sumhi/sumlo)
          If (DETECT(4).lt.-0.15) valid = .true.
          If (valid) Then
               If (DETECT(4).gt.SPECT) Then
                  STATUS = 'Local'
                  ichan(8) = ichan(8)+1
               Else
                  STATUS = 'Teleseism'
                  ichan(9) = ichan(9)+1
               Endif
          Endif
      Endif
c
c...  Continue Detection?
c
```

```
      If (DETN .and. qqp) th = tend
c
c...  Detection End?
c
      If (.not.big .and. DETN .and. .not.qqp) Then
         detend = .true.
         DETN = .false.
         th = tsrt
         saqout = .false.
         If (STATUS.eq.'Local' .or. STATUS.eq.'Teleseism') Then
             saqout = .true.
         Endif
         Call Report (CHANID,statim,STATUS,
     &            DETECT(2),DETECT(3),DETECT(1),saqout,DETECT(4))
      Endif
c
c...  Update LTA every 'R' STA's;
c
  150    Continue
         If (nsta.eq.R) Then
            If (DETN) Then
               If (valid) Then
                  LTA = e2sigd*cursta + sigdf*LTA
               Else
                  valid = .true.
               Endif
            Else
               LTA = e2sig *cursta + sigf *LTA
            Endif
            tsrt = TRNON*LTA
            tend = TRNOFF*LTA
         nsta = 0
         Endif
c
c...  Update start and end detection thresholds.
c
         th = tsrt
         If (DETN) th = tend
 1000 Continue
c
      Return
      End
```

```
rfil_(n,b,x,y)
int   *n;
float b[],x[],y[];

{
#define IRP 7
static float a[IRP] = {
        1.0000000e+00,
        0.0000000e+00, -3.0000000e+00,  0.0000000e+00,
          3.0000000e+00,  0.0000000e+00, -1.0000000e+00};

      register int i,j;
      float sumax,sumby;

      for (i = 0 ; i < *n ; i++) {

              sumax = x[i];
              for (j = 2 ; j < IRP ; j += 2)
                      sumax += a[j]*x[i-j];

              sumby = b[1]*y[i-1];
              for (j = 2 ; j < IRP ; j++)
                      sumby += b[j]*y[i-j];

              y[i] = sumax-sumby;
      }
}

#include <stdio.h>
toilet_()
{
      fflush(stdout);
      fflush(stderr);
      return;
}
```

SAMPLE OUTPUT

```
Unix DPS -- Version 80.232

Detecting on  7 Sites
Data Window: 15 Seconds
Sampling Rate: 10 Hertz
STA Interval:  0.5 Seconds
LTA      "   :  1.5    "
Detect on 3 of 3

    LTA Time Constant   Threshold
Normal:     30.0 Secs      2.0
Detection:  3.0 Secs       1.5

Filter Characteristics:
Order: 3      Type:1.2 - 3.0 Hz Bandpass
   N          A Prime(N)            B(N)
   0          1.000000e+ 0        1.000000e+ 0
   1        0.          e+ 0       -1.122158e+ 0
   2        -3.000000e+ 0         1.254692e+ 0
   3        0.          e+ 0       -8.377432e- 1
   4          3.000000e+ 0        6.884214e- 1
   5        0.          e+ 0       -2.241161e- 1
   6        -1.000000e+ 0         8.427375e- 2

FFT Parameters:
Number of Points: 64
Delta Time:       0.10000 Sec   Delta Frequency: 0.15625 Hz

Spectral Ratio Bands:
Low       7 ( 0.94 Hz) to    13 ( 1.88 Hz)
High     14 ( 2.03 Hz) to    25 ( 3.75 Hz)

log Ratio for Regional/Teleseismic test: 0.20

Spike Check Parameters
Temporal Coherency:  1.00 Sec
"Big"   Ratio:  1.50
"Small" Ratio:  2.00
Low Cutoff for Spikes:    3 ( 0.31 Hz)

Run will begin at first record
Run will  end  at last  record
SAQ File is L07419.saq
Index File is L07419.gi
Marker File is L07419.mk
Gram File is L07419.0.g
```

Channel Information

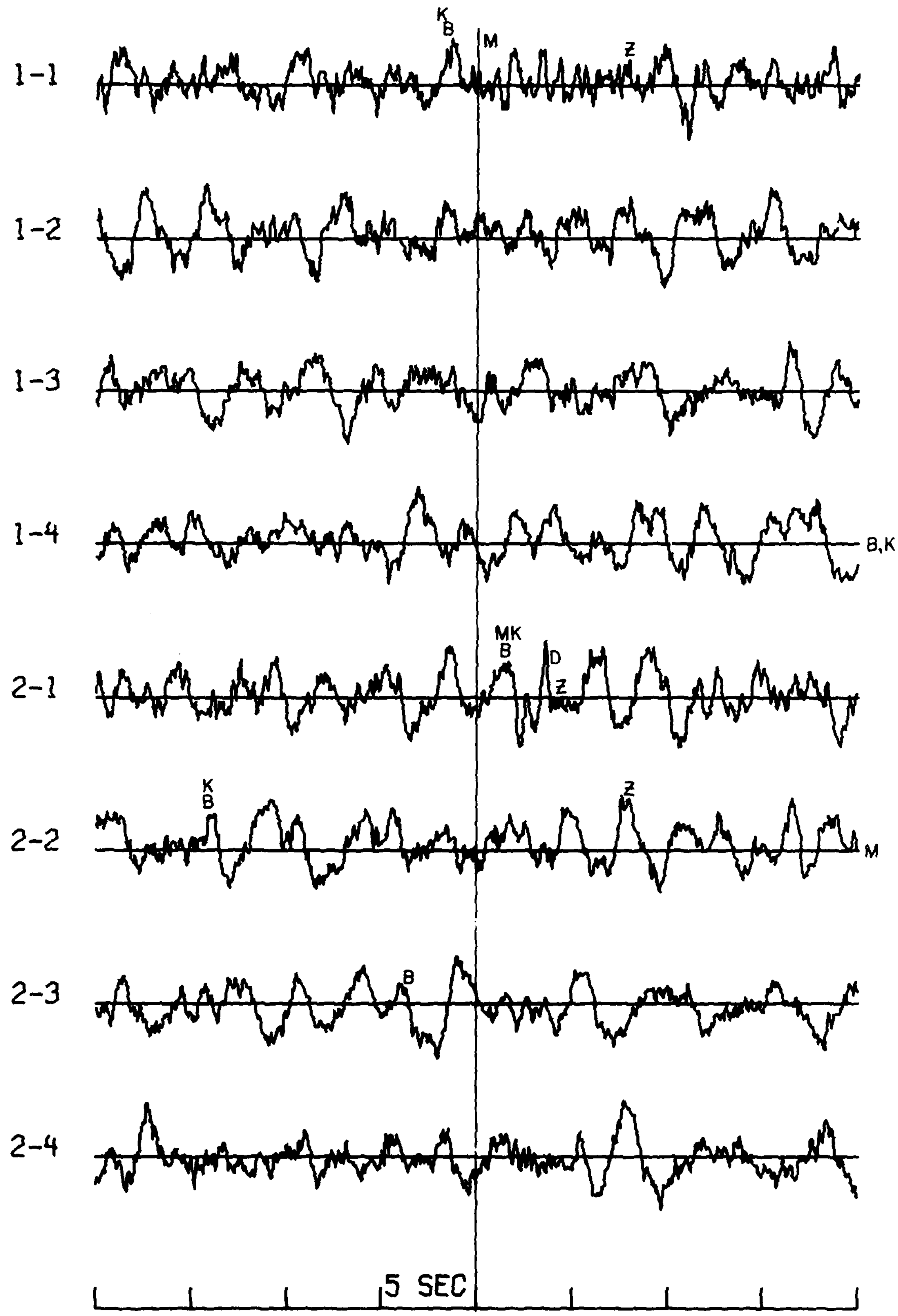
Site	Channel	Site #	DPS Ptr	Chan Ptr	Chan Incr	Calib	Delay	Display
ALK	20SHBFAK	3	307	13	32	0.10470	-4.00	Off
ALK	20SHUCAK	3	307	16	32	0.08860	0.	Off
ALK	20SHCNAK	3	307	17	32	0.10480	0.	Off
ALK	20SHNJAK	3	307	18	32	0.11570	0.	Off
ALK	20IHTNAK	3	307	19	32	0.21860	0.	Off
PWY	20SHP999	4	710	13	28	0.10000	-4.00	Off
ALK	20IHATAK	3	307	20	32	0.61600	0.	Off

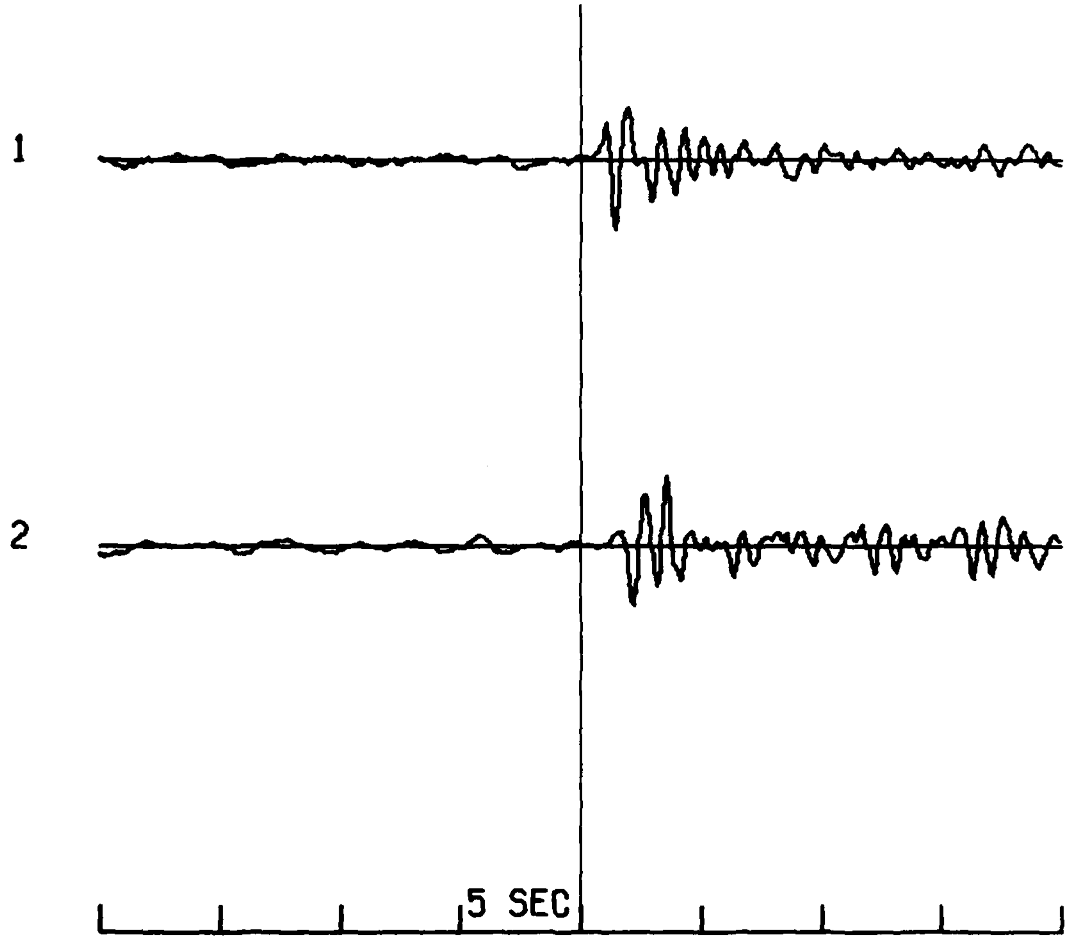
```
Tape L07419 starts at 79/091/06:39:44
First data at  91/06:39:44
DP started at  91/06:39:44
Record Number    1
```

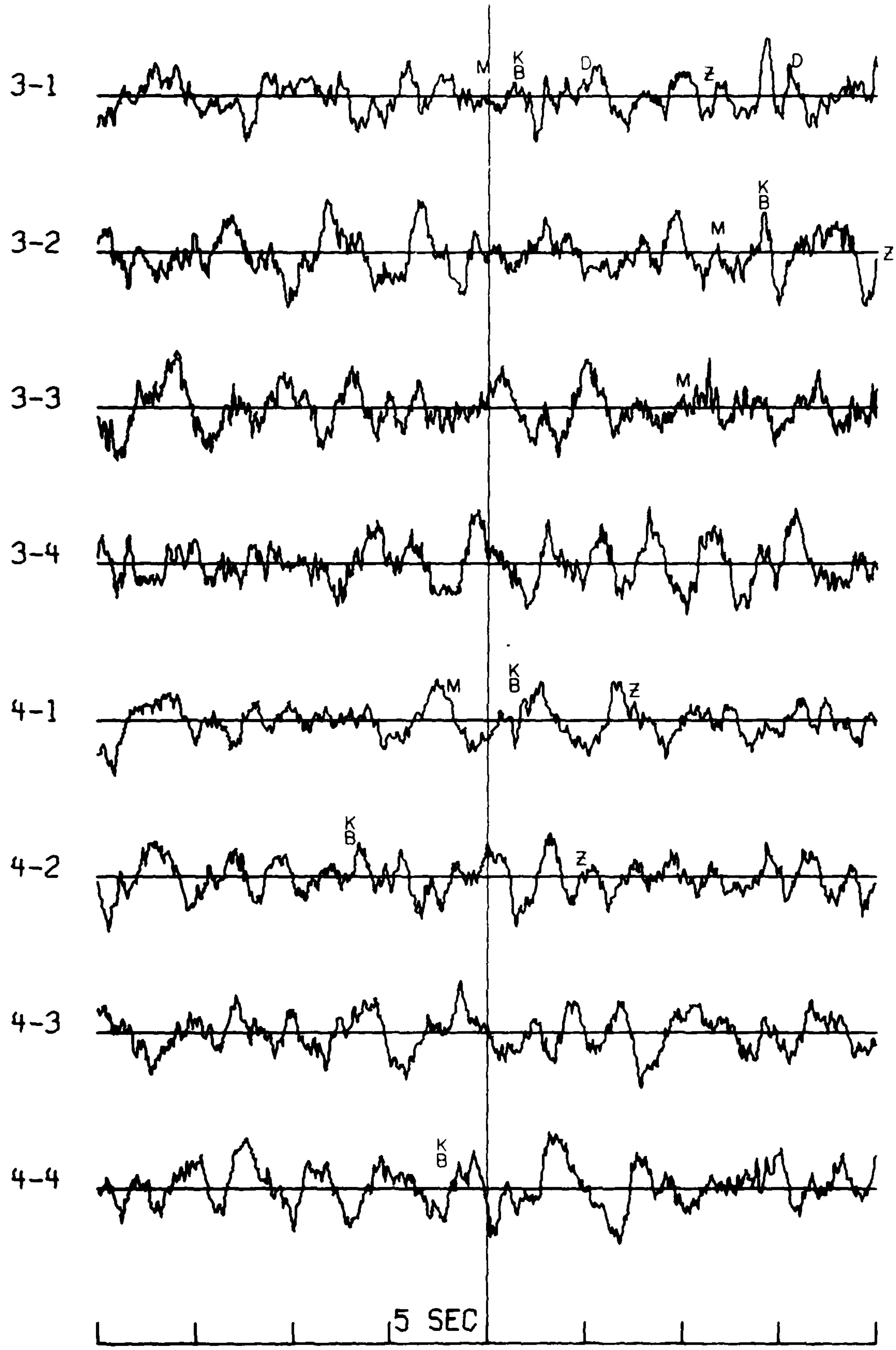
Name	Time	Status	STA	LTA	STA/LTA	log SR	Max Freq	
BFAK	06:39:44.5	Initial	0	7	0.	0.	0.	
UCAK	06:39:44.5	Initial	0	42	0.	0.	0.	
CNAK	06:39:44.5	Initial	0	40	0.	0.	0.	
NJAK	06:39:44.5	Initial	0	28	0.	0.	0.	
TNAK	06:39:44.5	Initial	0	23	0.	0.	0.	
P999	06:39:44.5	Initial	0	6	0.	0.	0.	
ATAK	06:39:44.5	Initial	0	45	0.	0.	0.	
BFAK	06:39:47.7	Teleseism	14	6	2.29	-0.60	0.78	1
P999	06:39:45.6	Teleseism	13	5	2.73	-0.47	0.63	2
P999	06:40:22.3	Teleseism	13	5	2.66	-0.34	0.63	3
N01	06:41:19	Data Gap						
ATAK	06:41:14.8	Teleseism	74	32	2.33	-1.01	0.16	4
N01	06:41:37	Data Gap						
TNAK	06:41:31.4	Teleseism	50	20	2.47	-0.76	0.31	5
N01	06:44:05	Data Gap						
N01	06:44:25	Data Gap						
BFAK	06:44:24.0	Teleseism	16	7	2.34	-0.62	0.63	6
TNAK	06:44:22.7	Spike 1	145	27	5.32	0.06	0.63	
ATAK	06:44:32.3	Teleseism	87	30	2.88	-0.86	0.63	7
BFAK	06:45:11.1	Teleseism	23	8	2.73	-0.77	0.94	8
N01	06:45:50	Data Gap						
N01	06:46:12	Data Gap						
UCAK	06:45:49.9	Spike_1	2866	149	19.22	0.23	0.31	
P999	06:45:53.8	Teleseism	11	5	2.13	-0.24	0.78	9
NJAK	06:47:45.9	Spike_1	38	16	2.39	-0.01	0.47	
TNAK	06:48:11.3	Teleseism	50	19	2.60	-0.68	0.78	10
ATAK	06:48:11.1	Teleseism	72	28	2.57	-0.83	0.78	11
NJAK	06:49:14.7	Teleseism	46	20	2.33	0.03	0.31	12
BFAK	06:49:17.3	Teleseism	25	9	2.86	-0.17	0.78	13
NJAK	06:49:24.7	Teleseism	82	32	2.56	0.07	0.16	14
NJAK	06:49:30.3	Teleseism	99	37	2.68	0.10	0.16	15
TNAK	06:49:55.3	Teleseism	56	21	2.68	-0.86	0.31	16
P999	06:50:05.9	Teleseism	11	5	2.12	-0.16	0.78	17
P999	06:50:15.3	Teleseism	16	7	2.52	-0.37	0.63	18
P999	06:50:24.7	Teleseism	24	8	2.96	-0.68	0.94	19
ATAK	06:50:34.1	Teleseism	63	30	2.11	-0.65	0.47	20
N01	06:50:52	Data Gap						
NJAK	06:51:16.3	Teleseism	59	21	2.82	-0.34	0.31	21
BFAK	06:51:45.6	Teleseism	26	8	3.16	-0.67	0.63	22
CNAK	06:51:56.4	Teleseism	41	17	2.47	-0.28	0.31	23
TNAK	06:51:56.7	Teleseism	55	21	2.60	-0.42	0.31	24
N01	06:52:27	Data Gap						
N01	06:53:04	Data Gap						
P999	06:53:03.6	Teleseism	11	5	2.17	-0.26	1.09	25

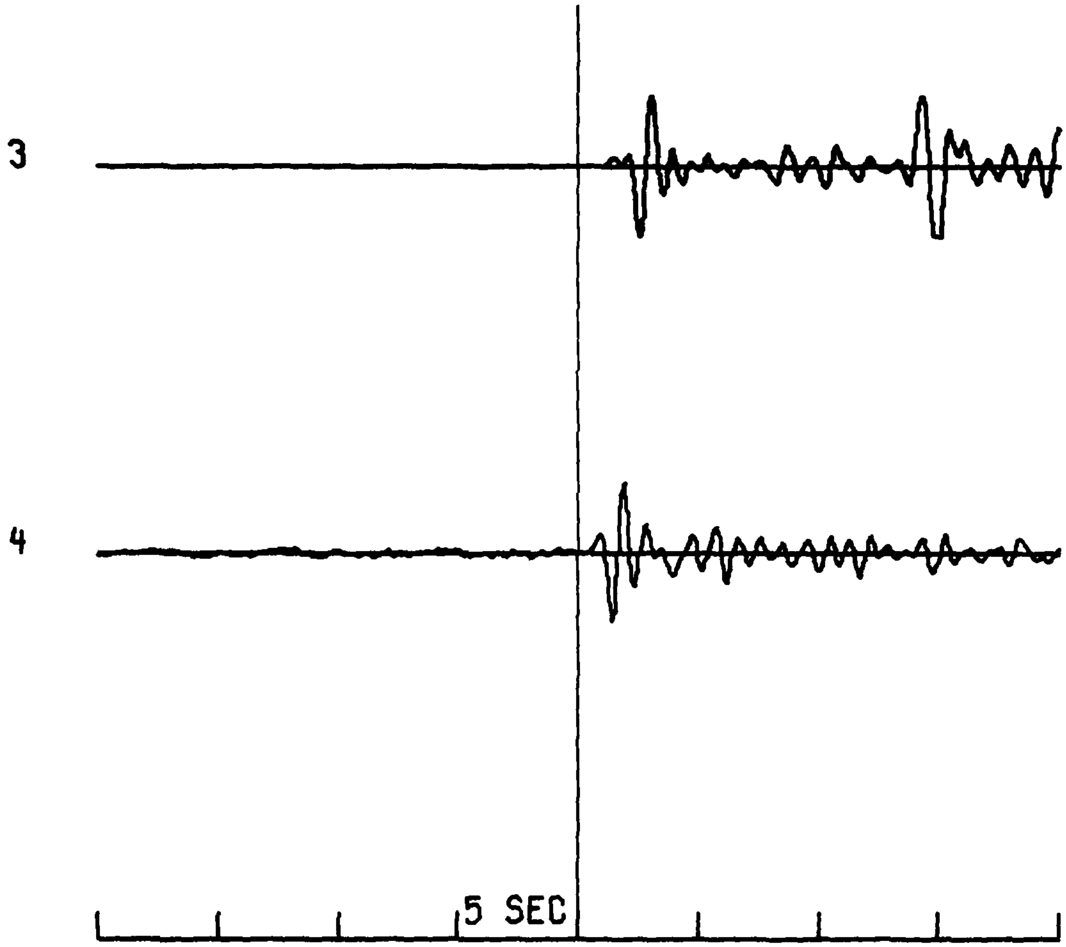
APPENDIX V

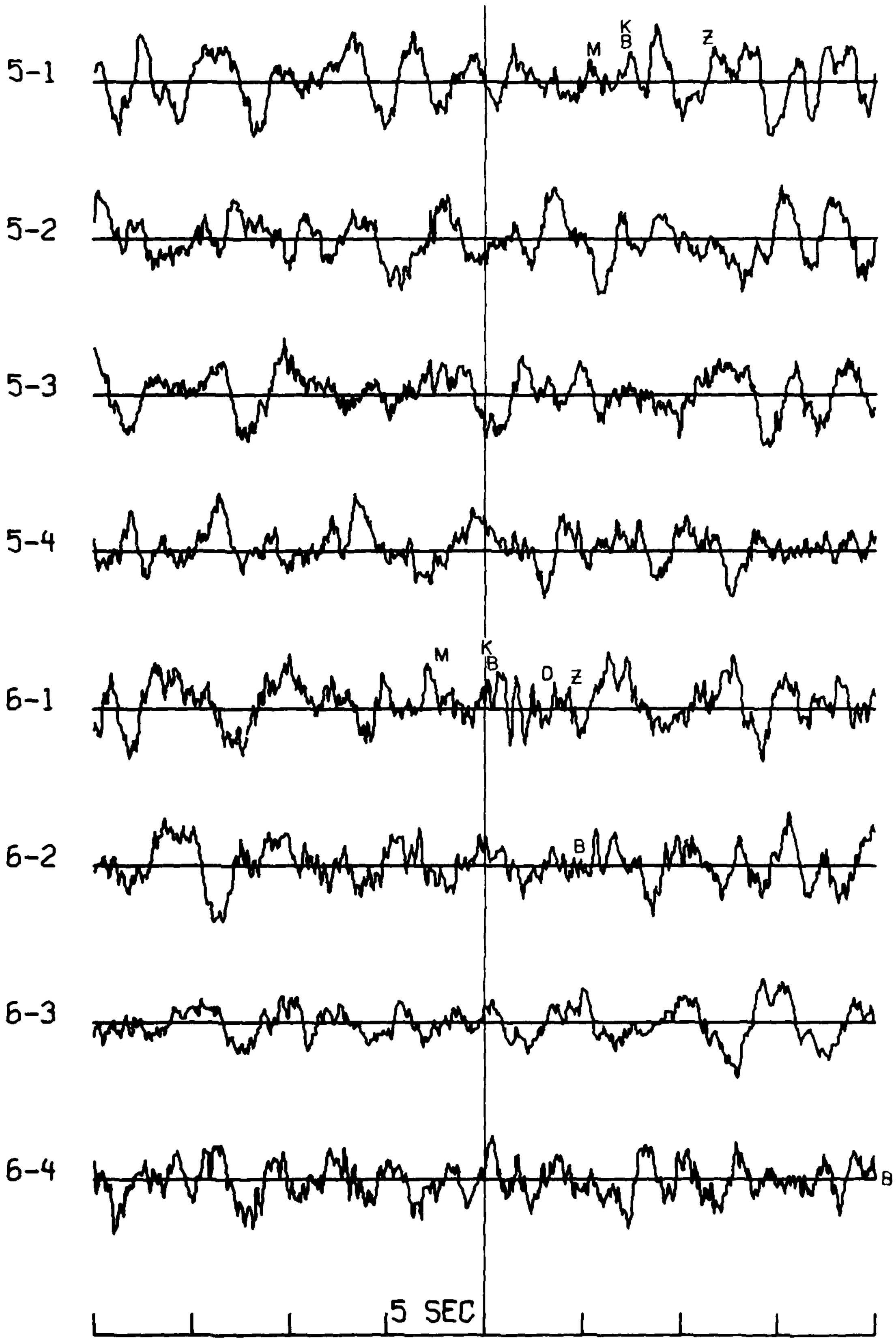
PWY Waveform and Detection Markers

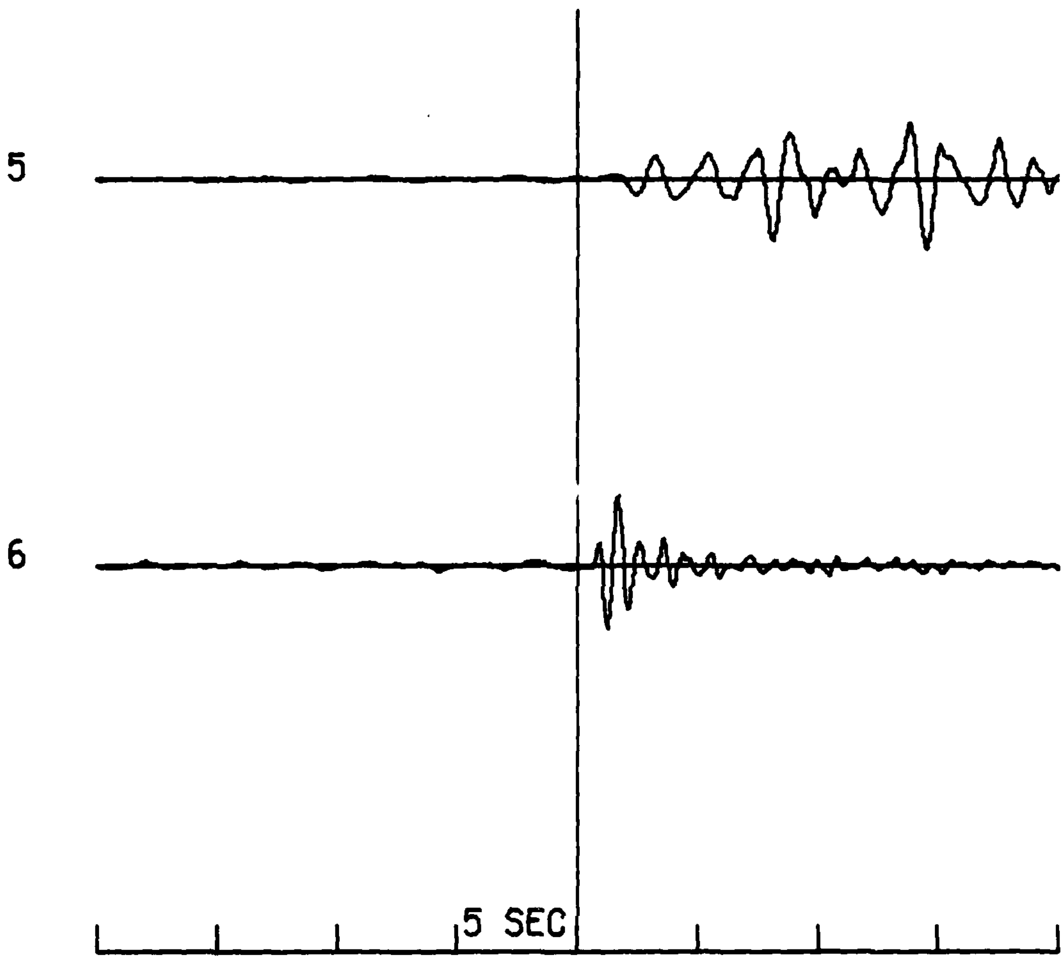

1-1
1-2
1-3
1-4
2-1
2-2
2-3
2-4
K
B
M
Z
B,K
MK
B
D
Z
K
B
Z
M
B
5 SEC

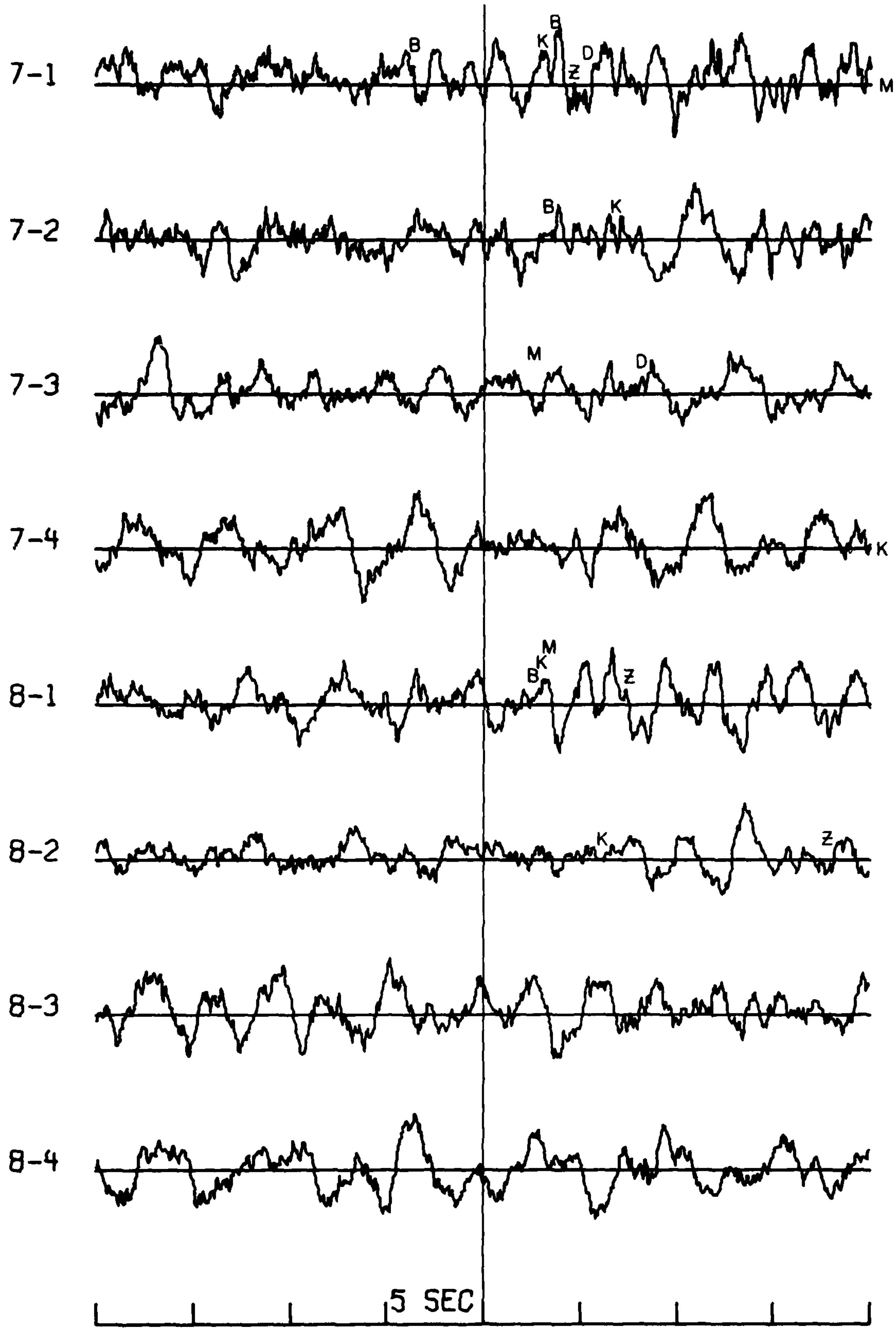

1
2
5 SEC

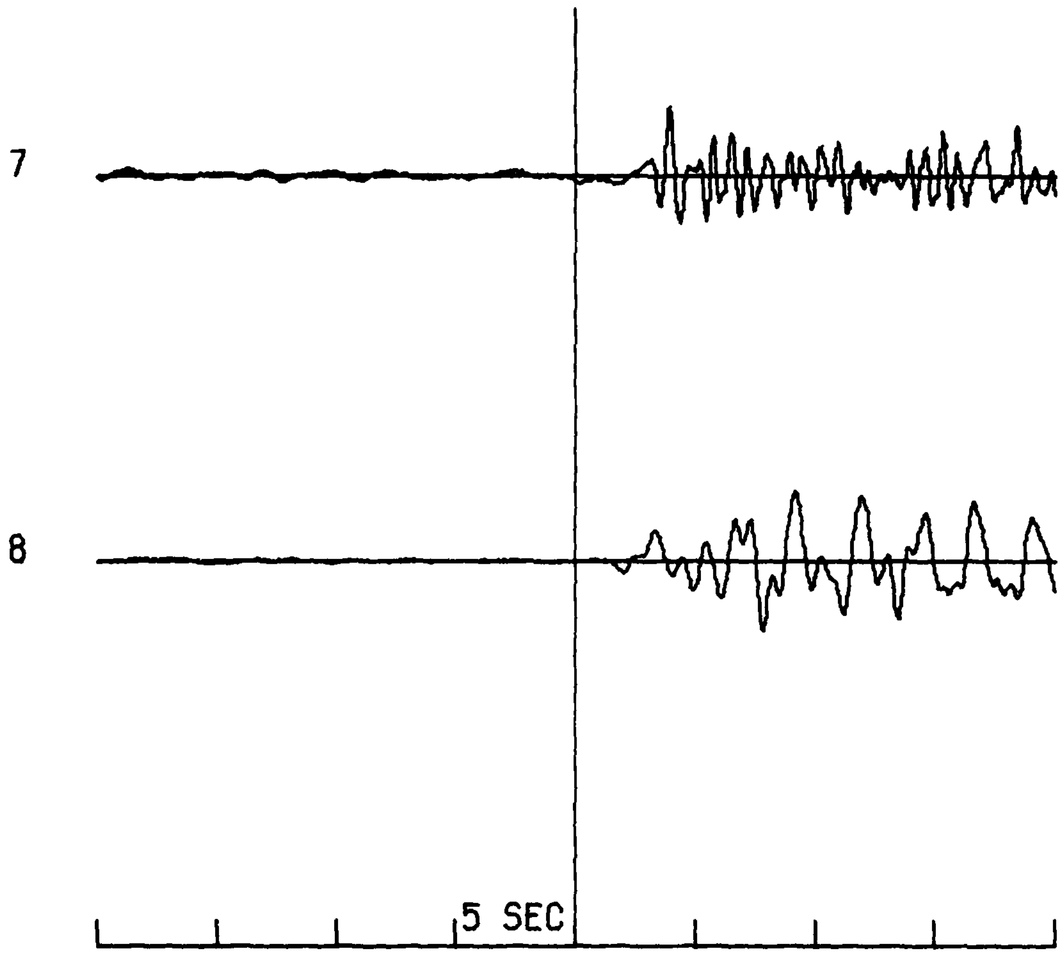

3-1
M
K
B
D
Z
D
3-2
K
B
M
Z
3-3
M
3-4
4-1
M
K
B
Z
4-2
K
B
Z
4-3
4-4
K
B
5 SEC

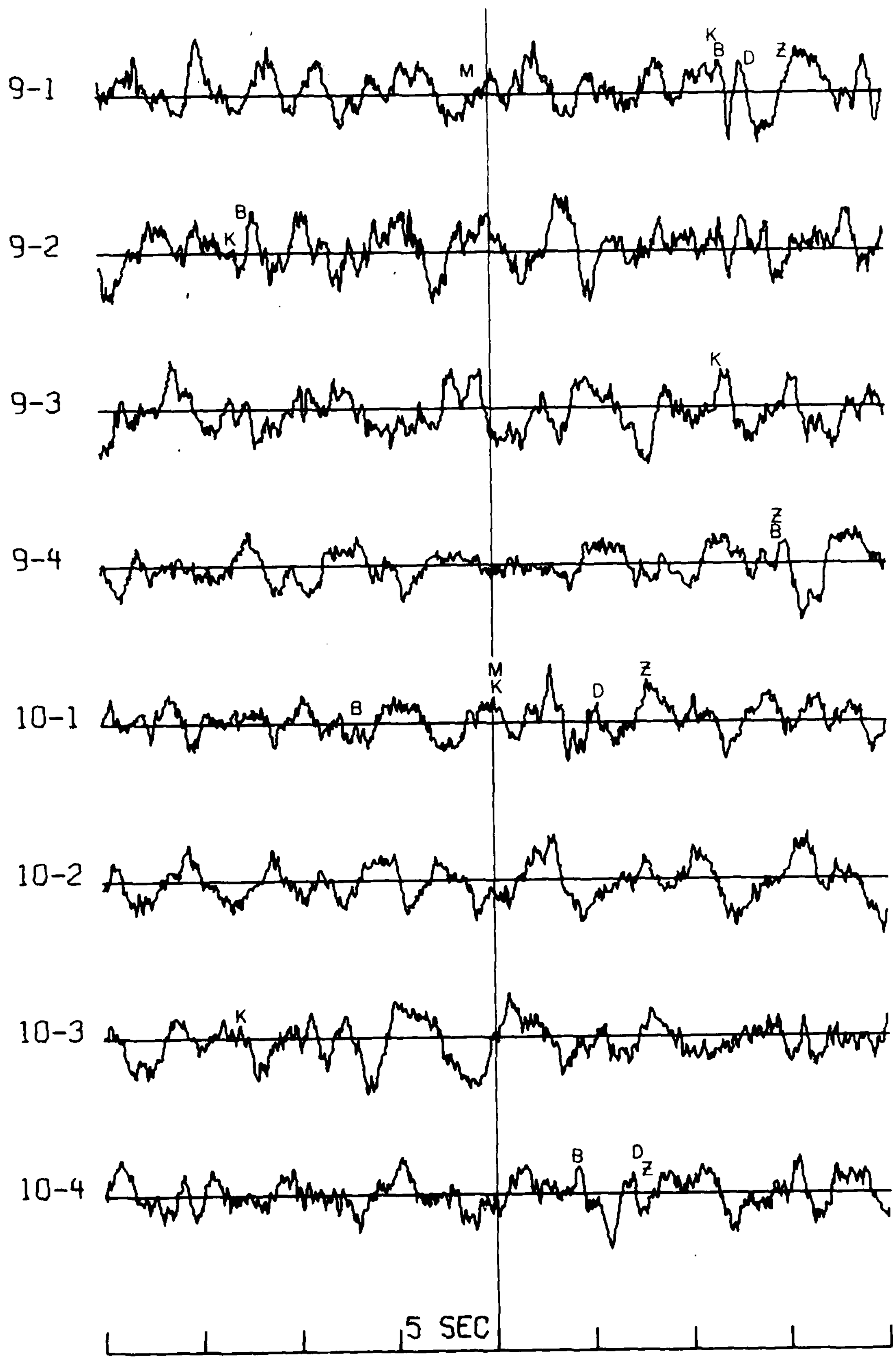

3
4
5 SEC


5-1
M
K
B
Z
5-2
5-3
5-4
6-1
M
K
B
D
Z
6-2
B
6-3
6-4
B
5 SEC


5
6
5 SEC


7-1
B
K
B
Z
D
M
7-2
B
K
7-3
M
D
7-4
K
8-1
B
K
M
Z
8-2
K
Z
8-3
8-4
5 SEC


7
8
5 SEC


9-1
9-2
9-3
9-4
10-1
10-2
10-3
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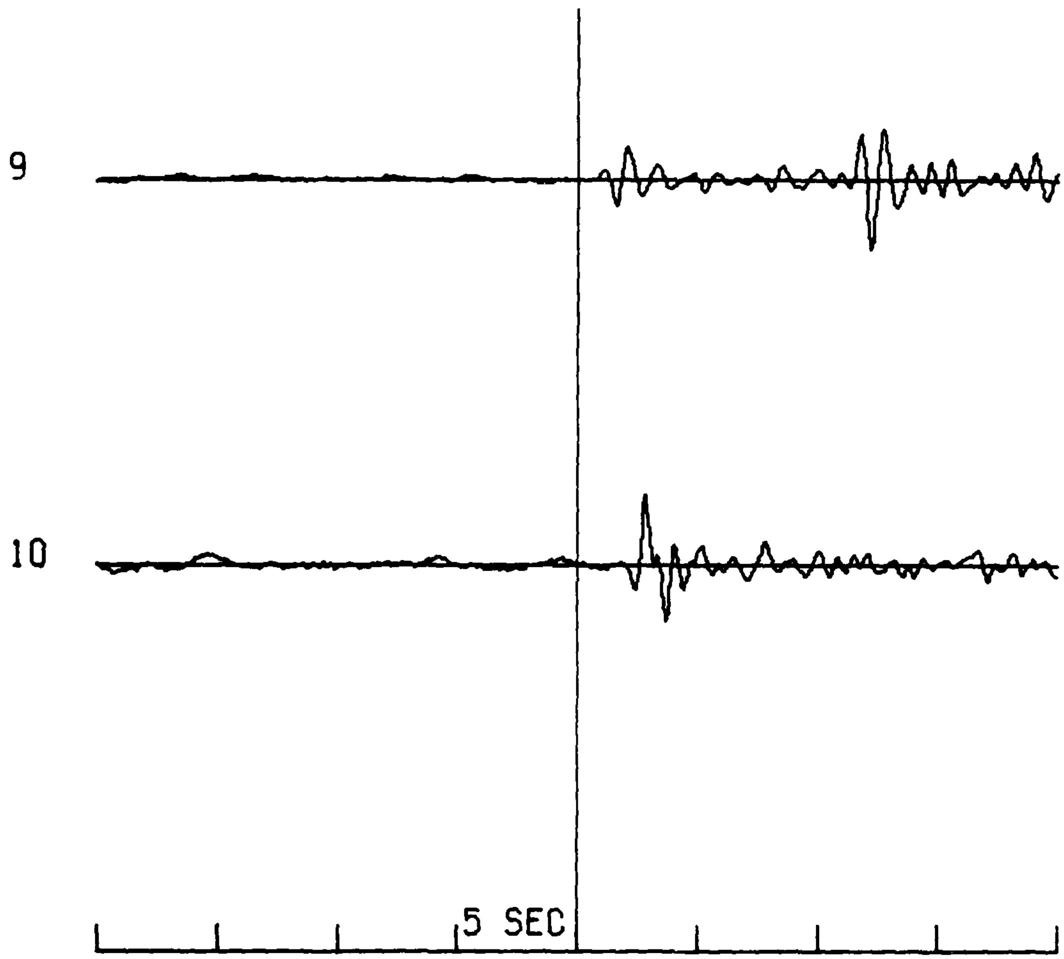

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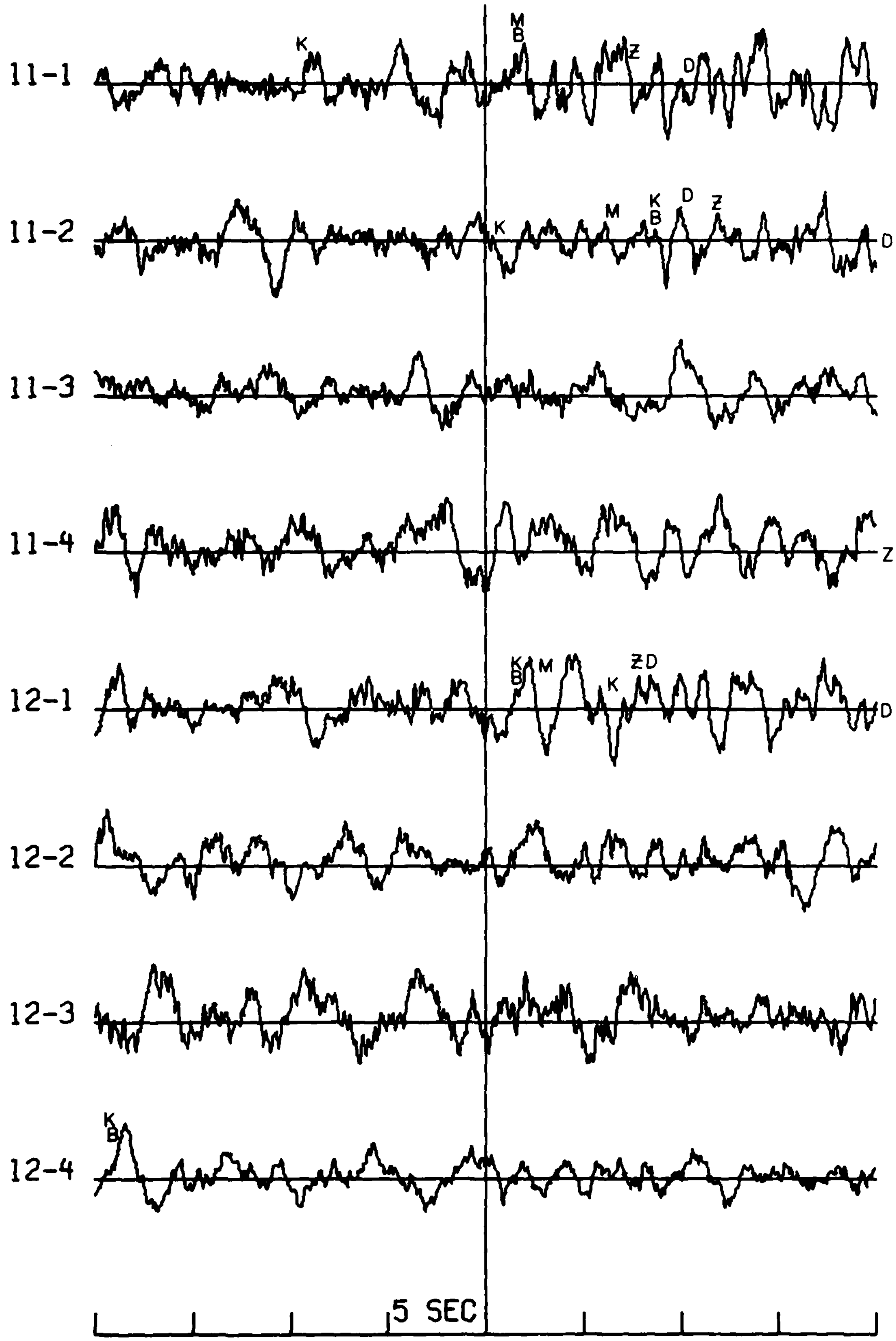
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D
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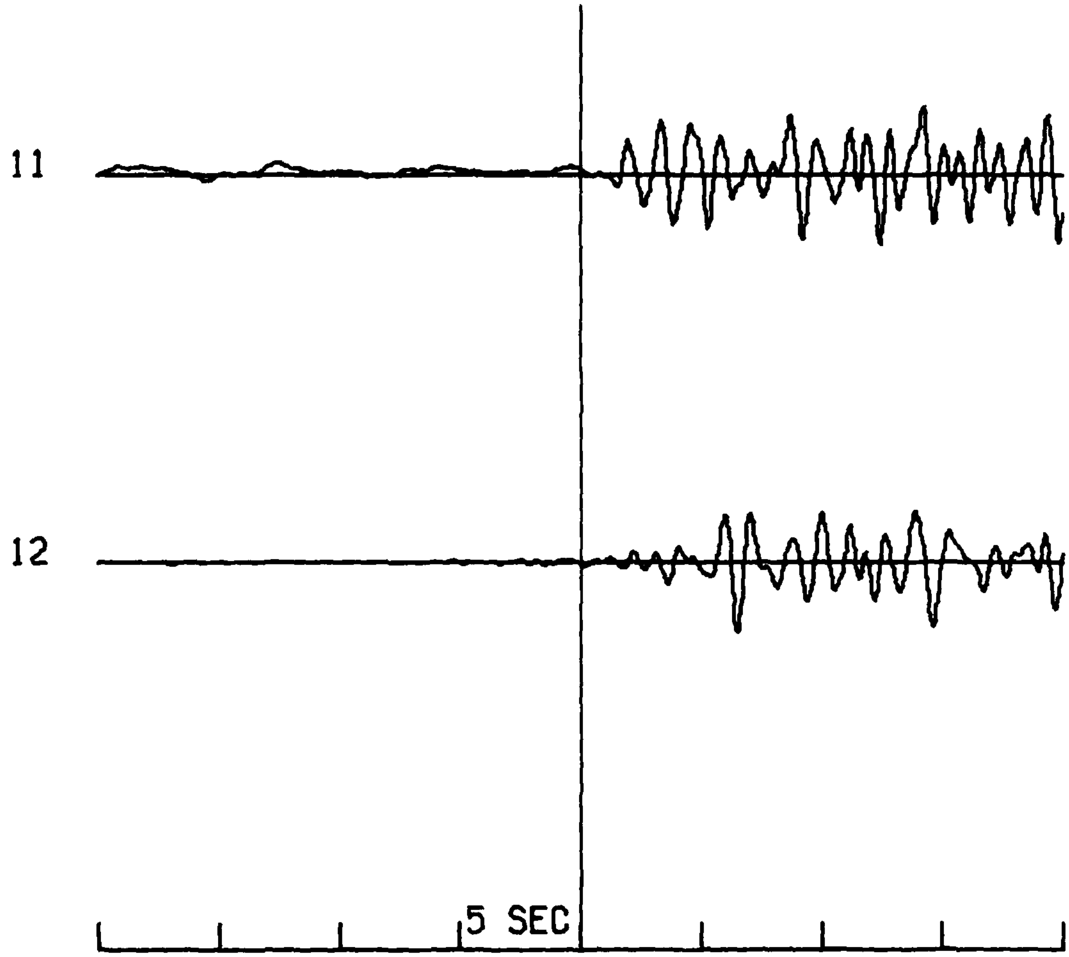
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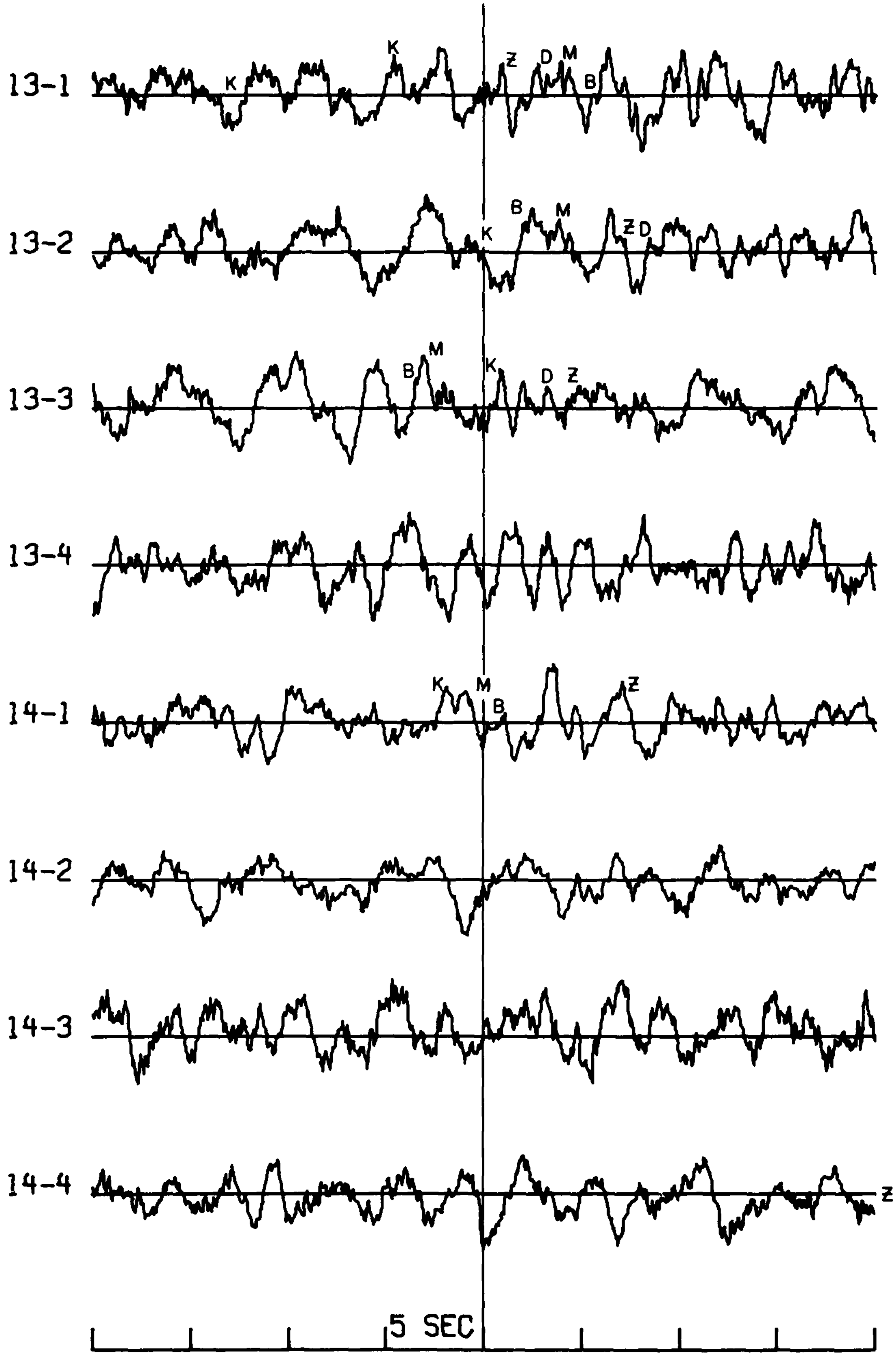
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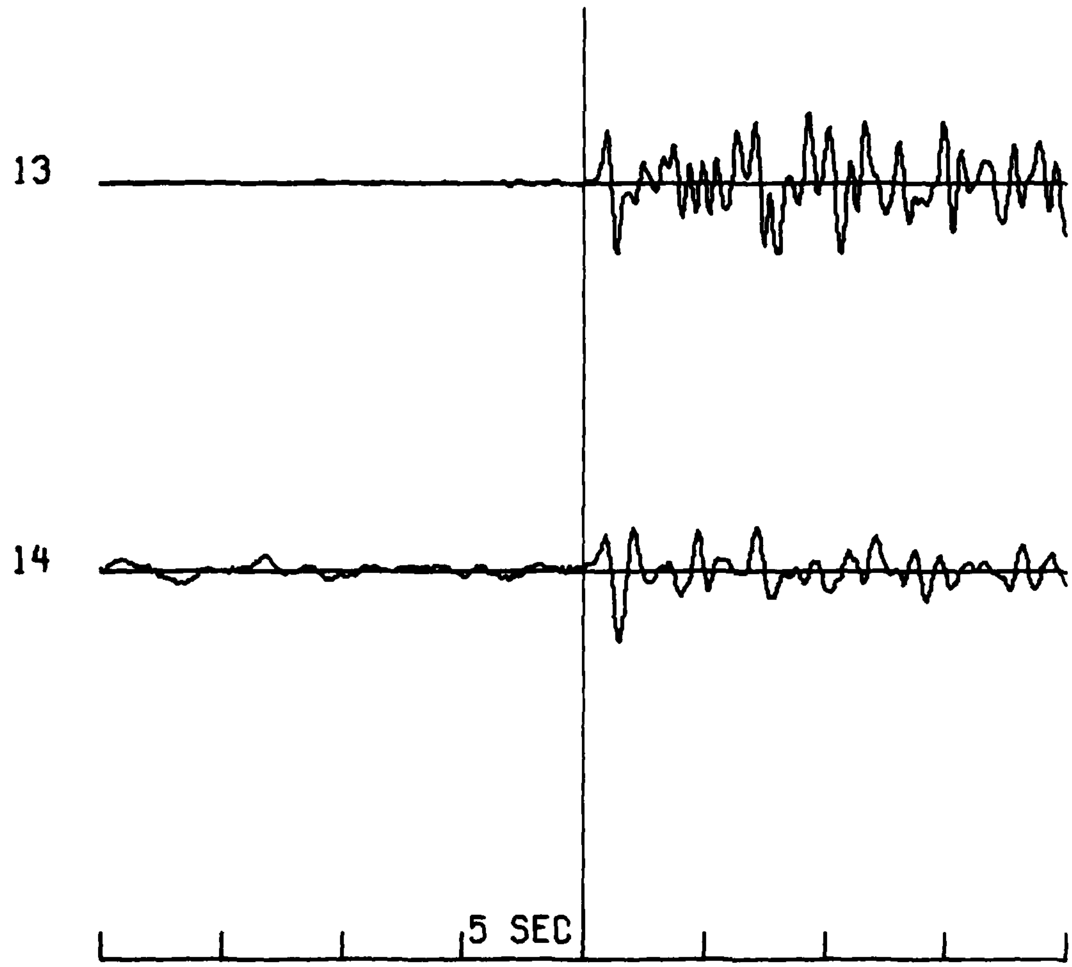
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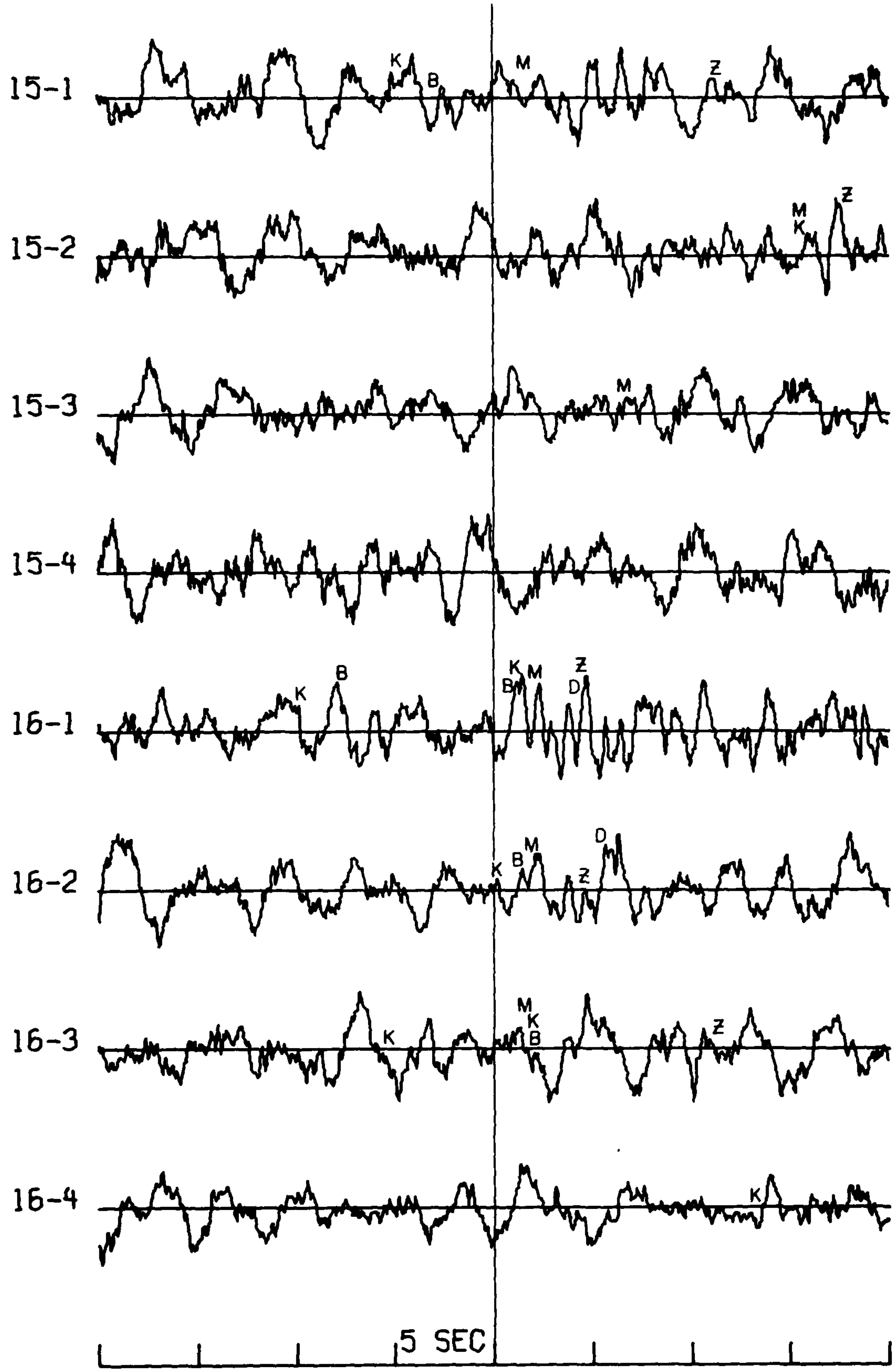
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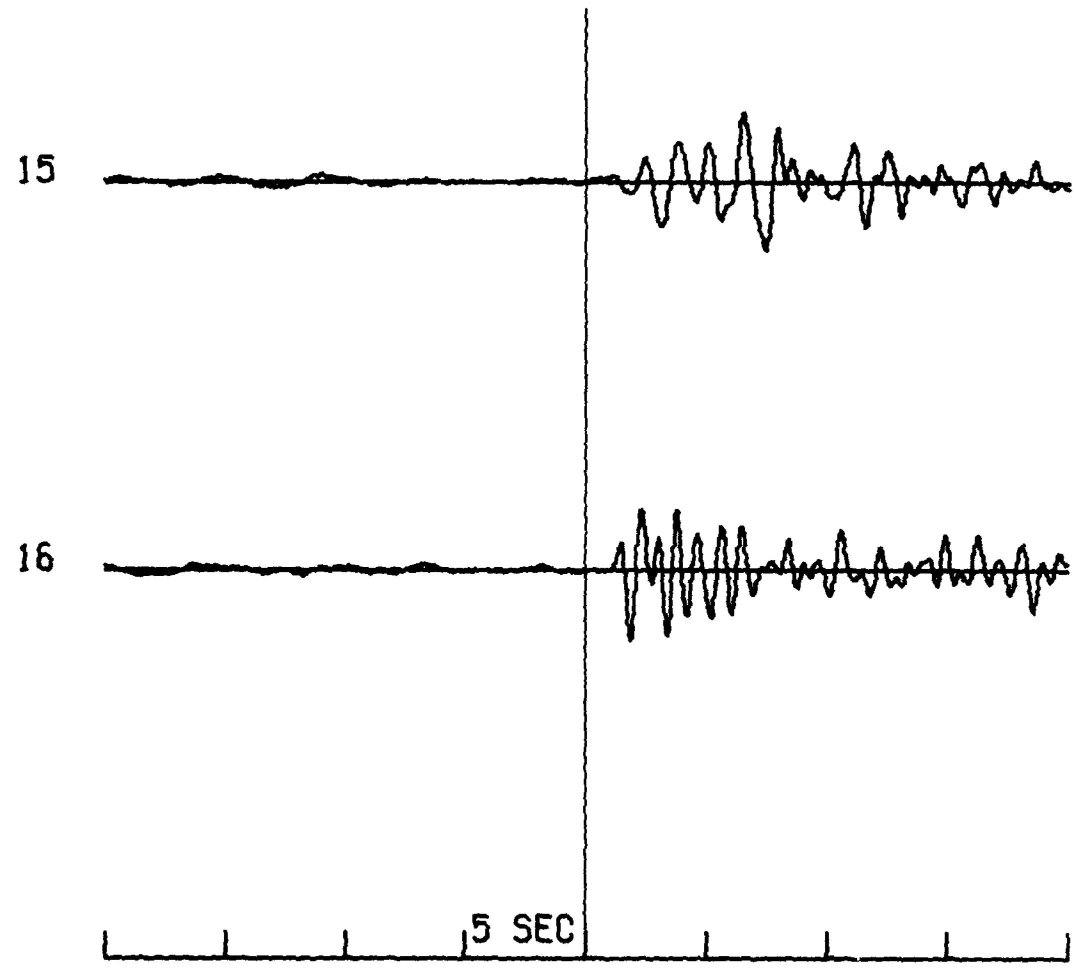
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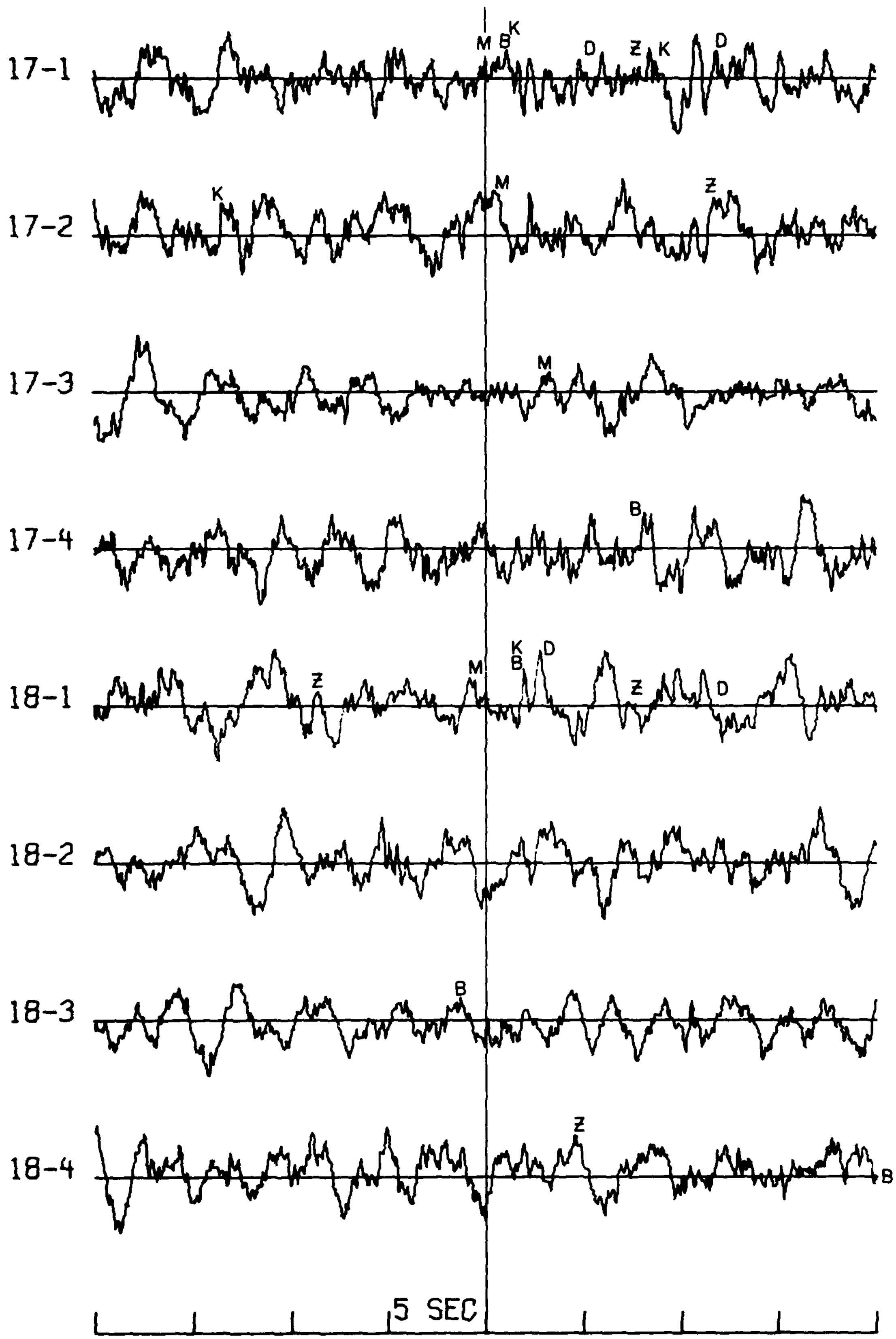
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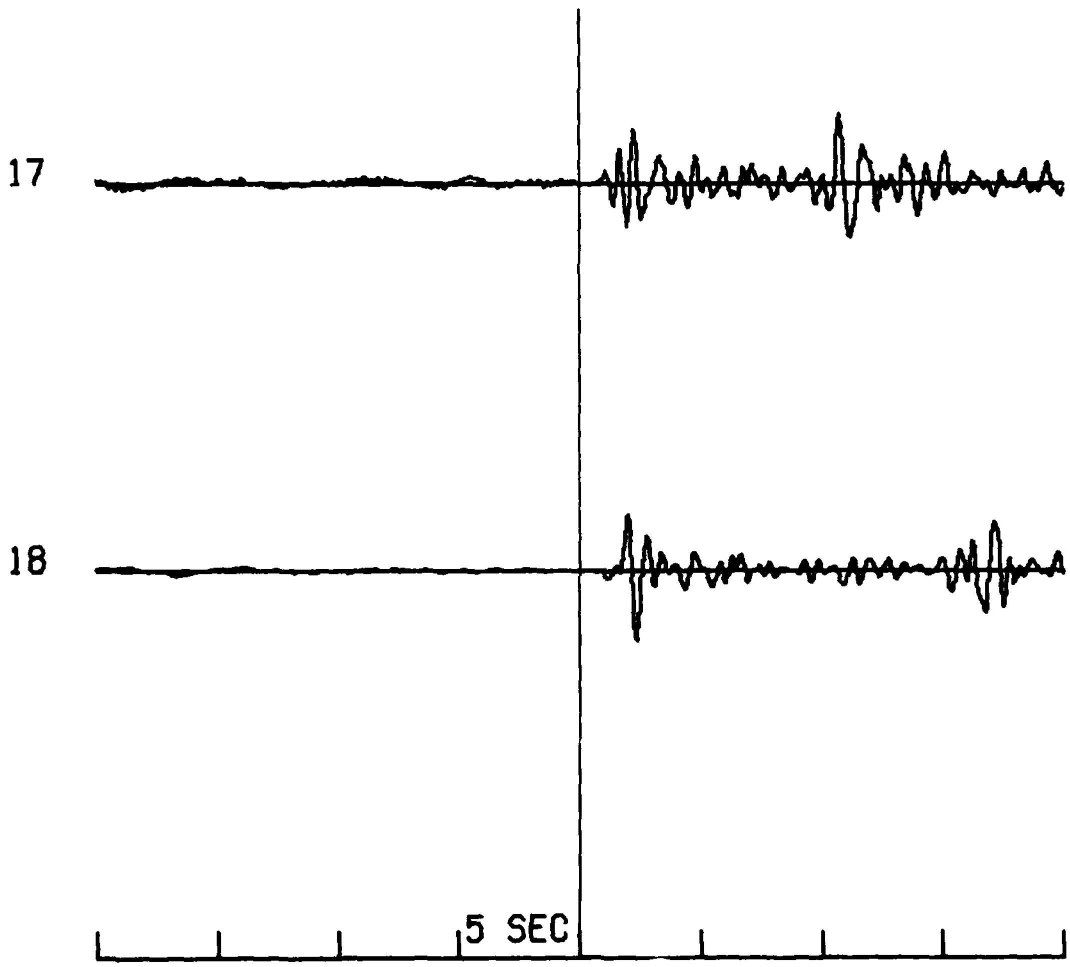

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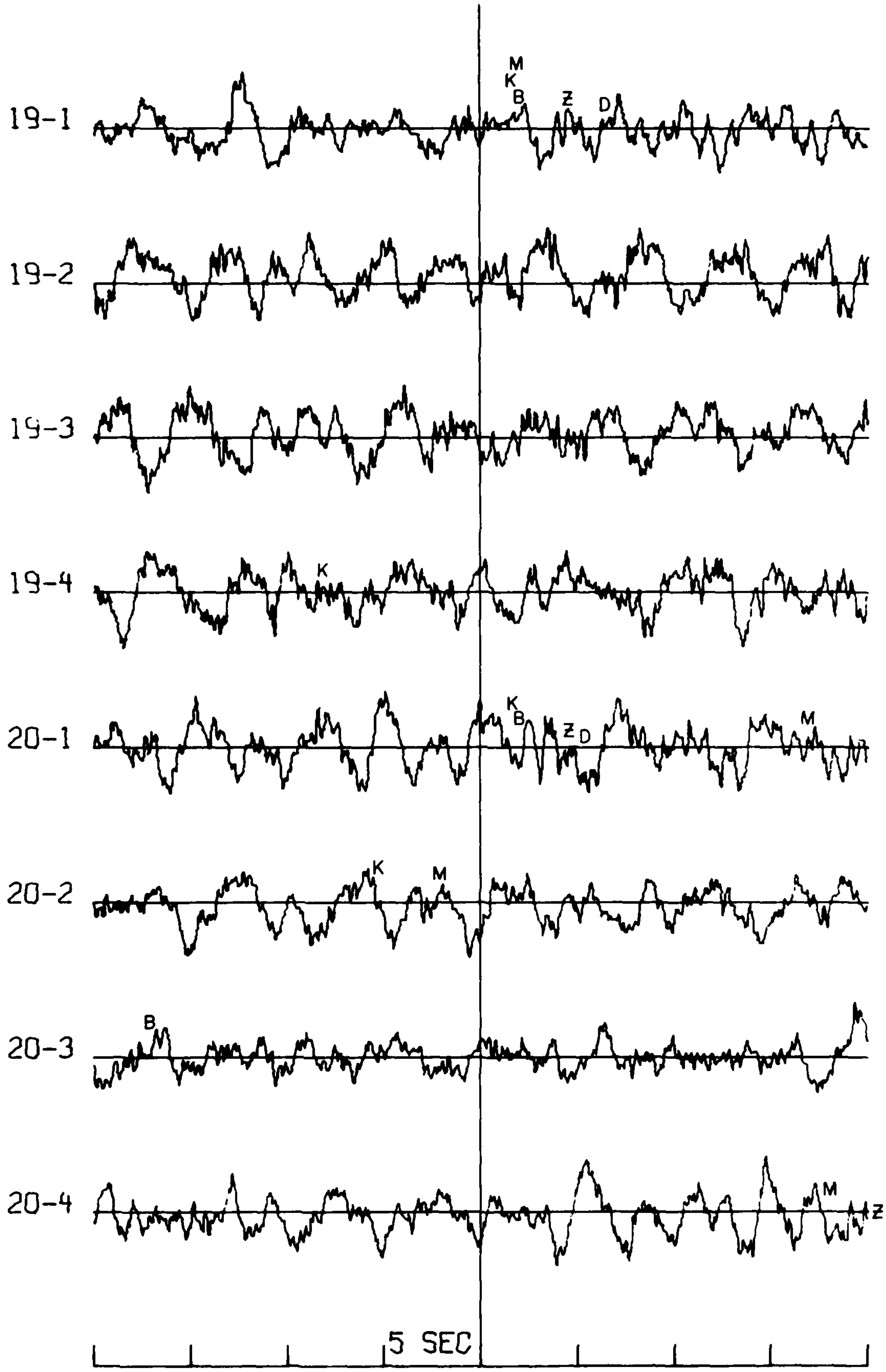
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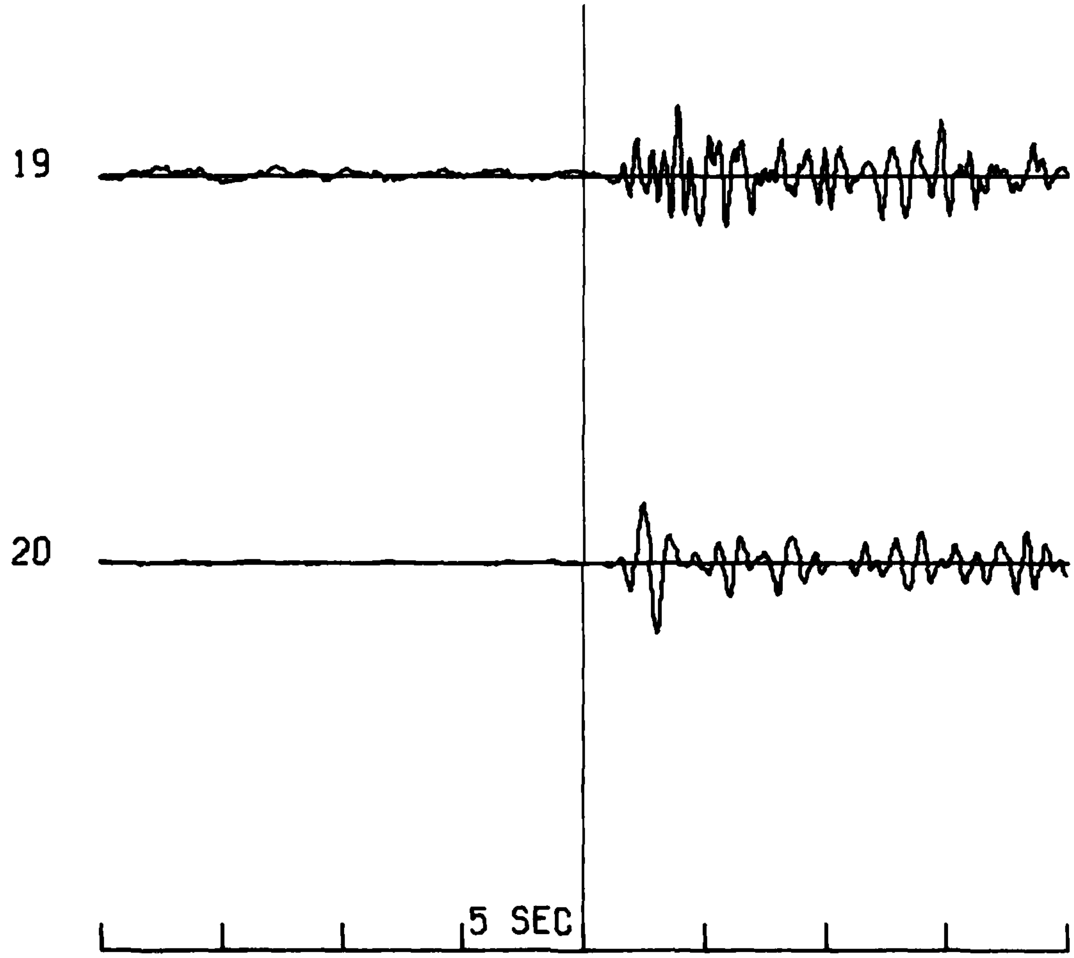
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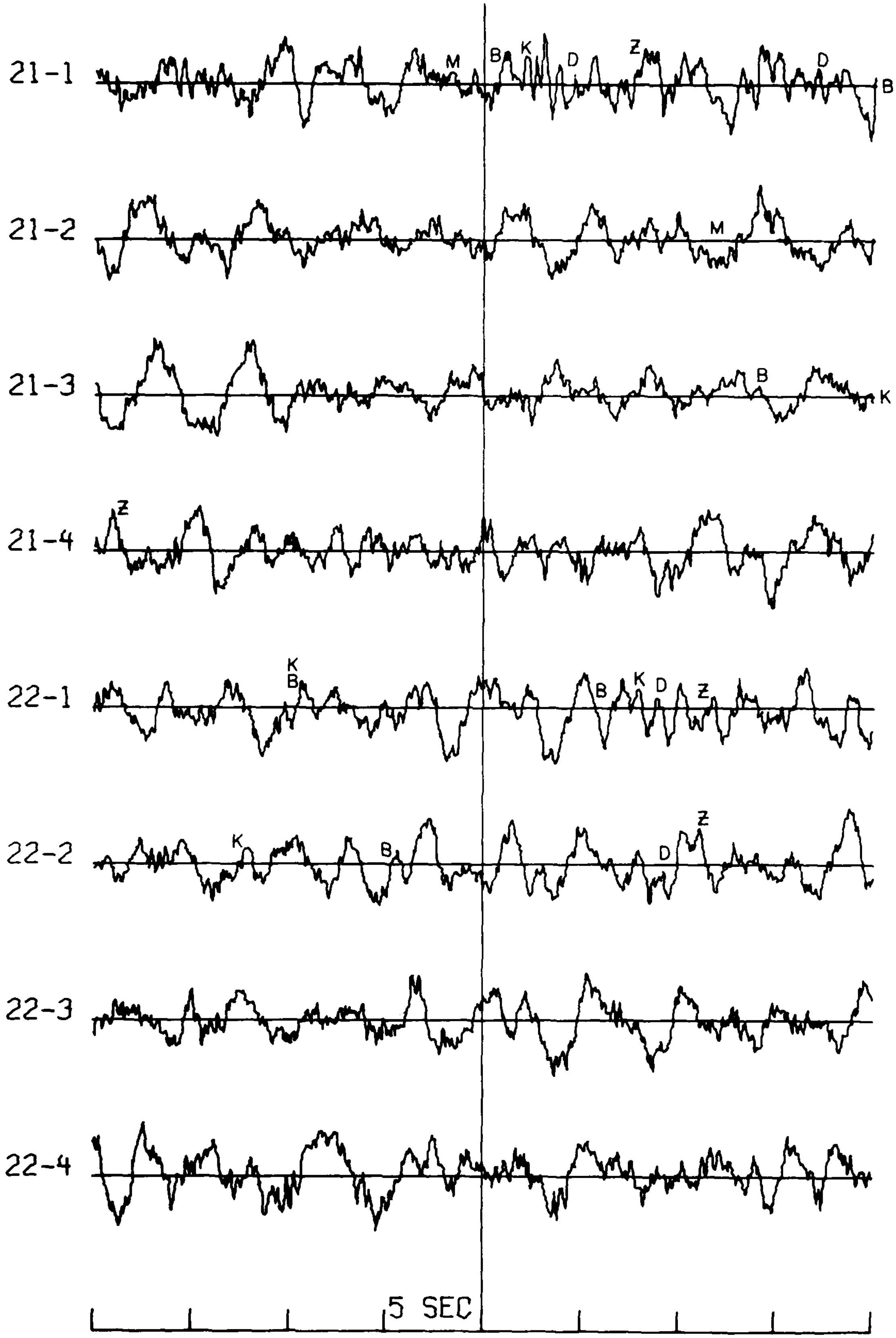
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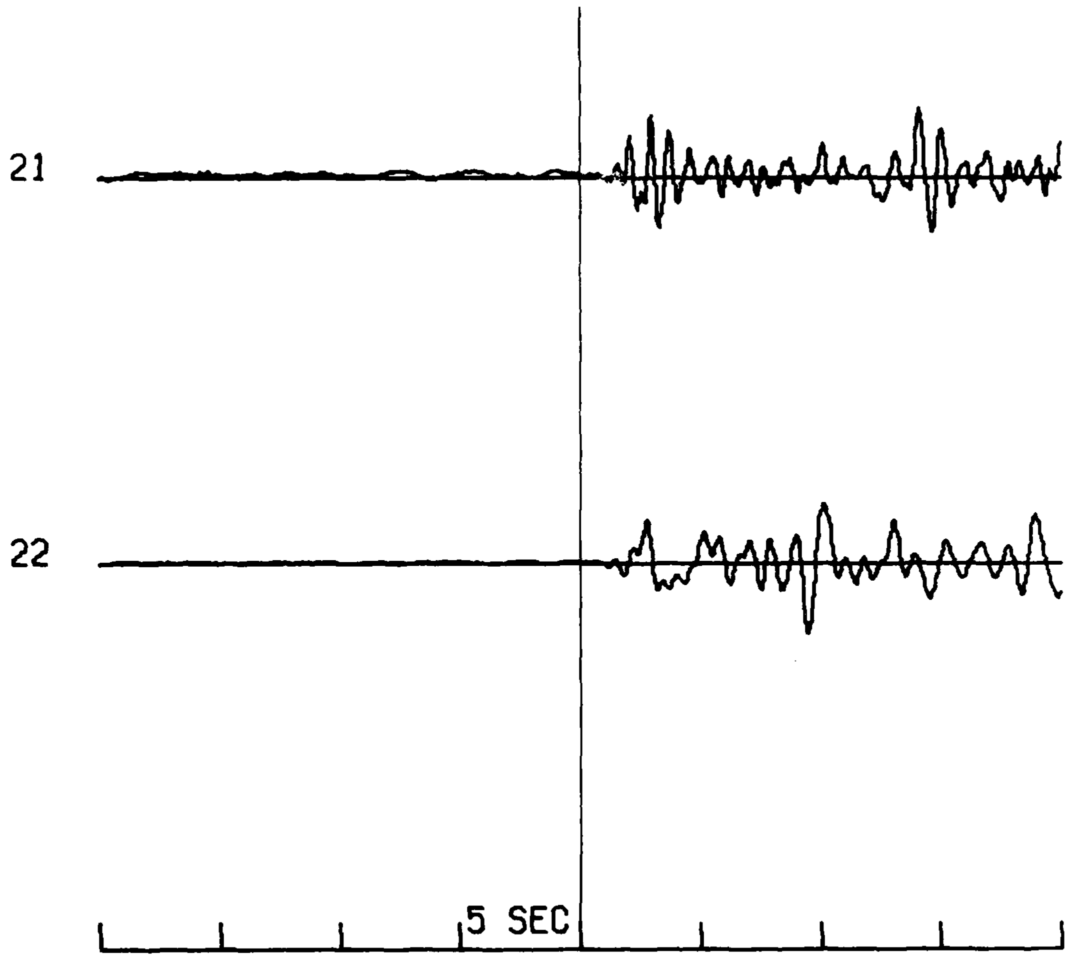
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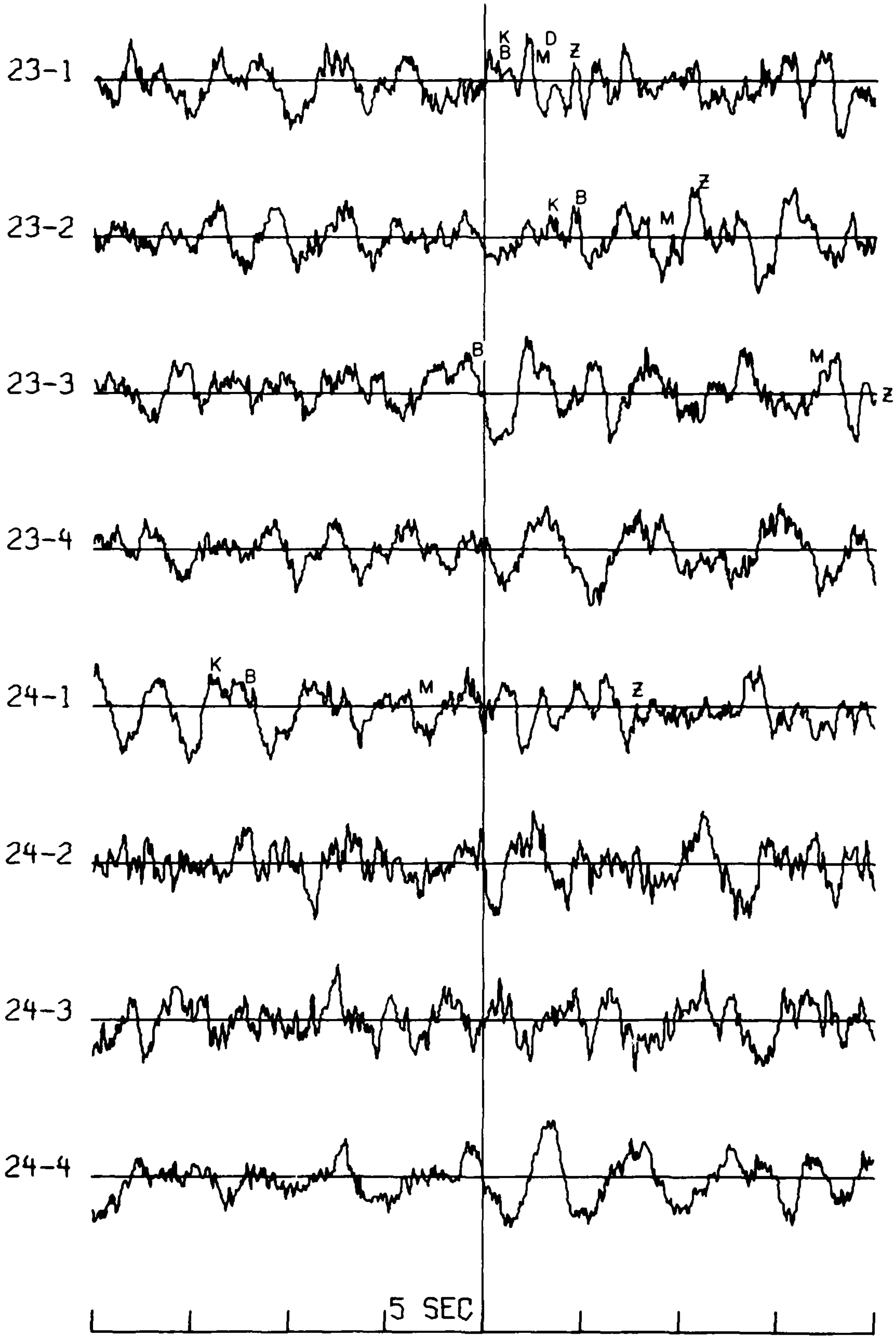
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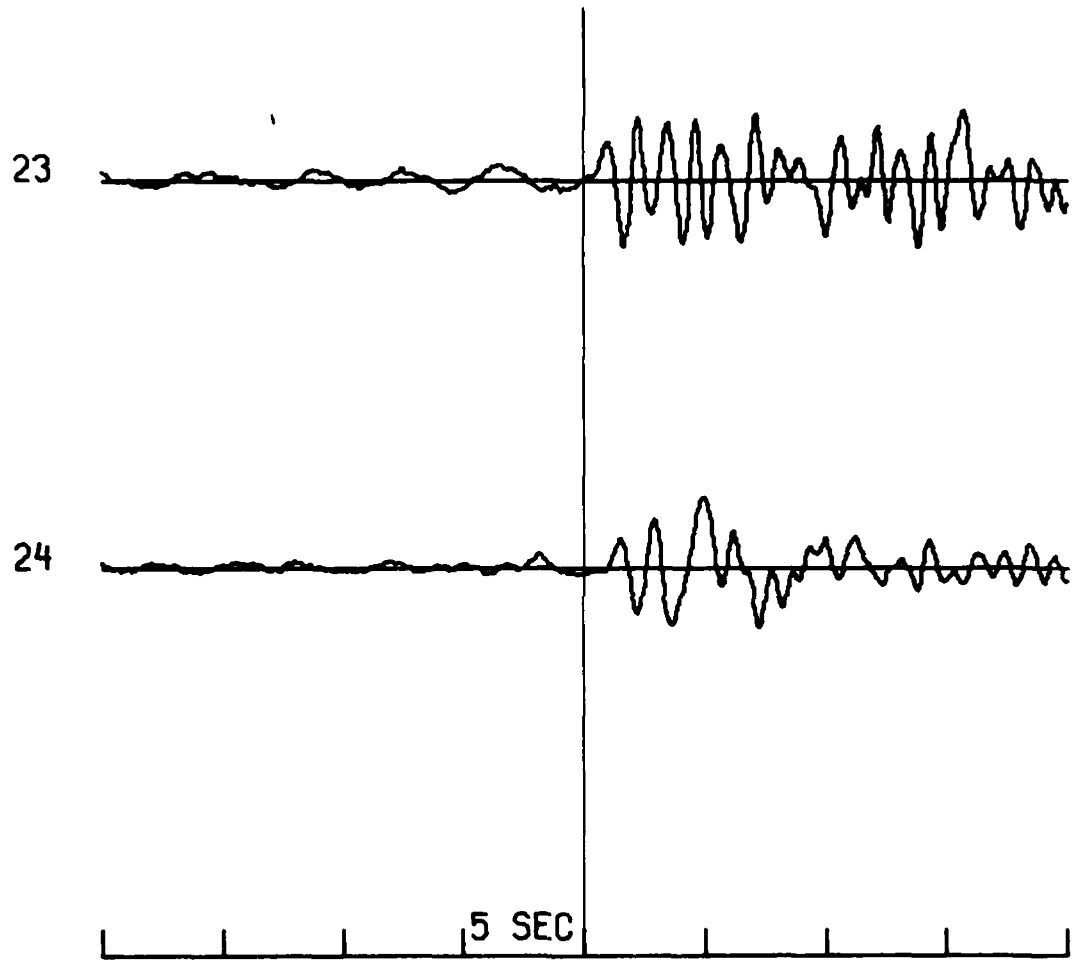
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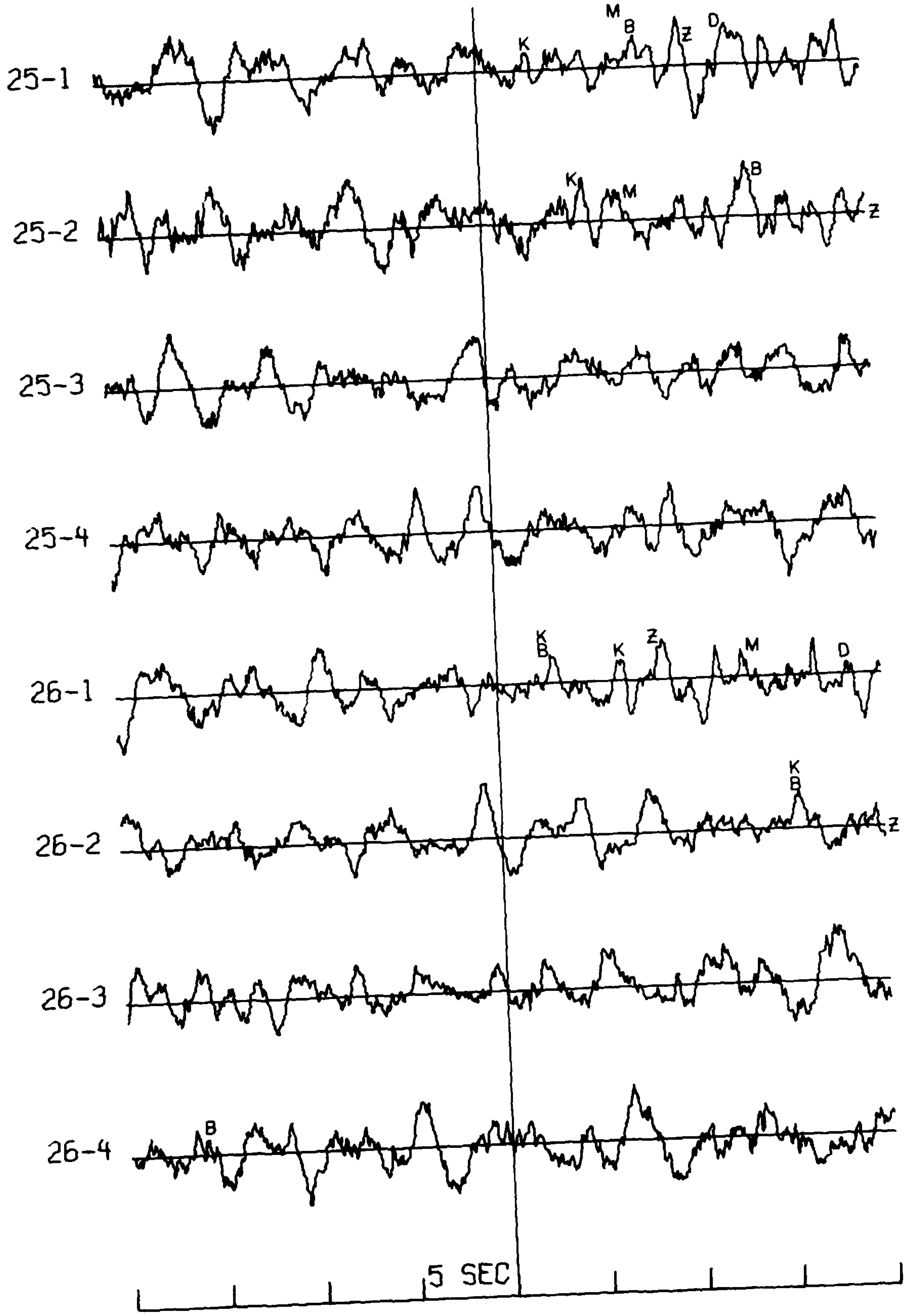
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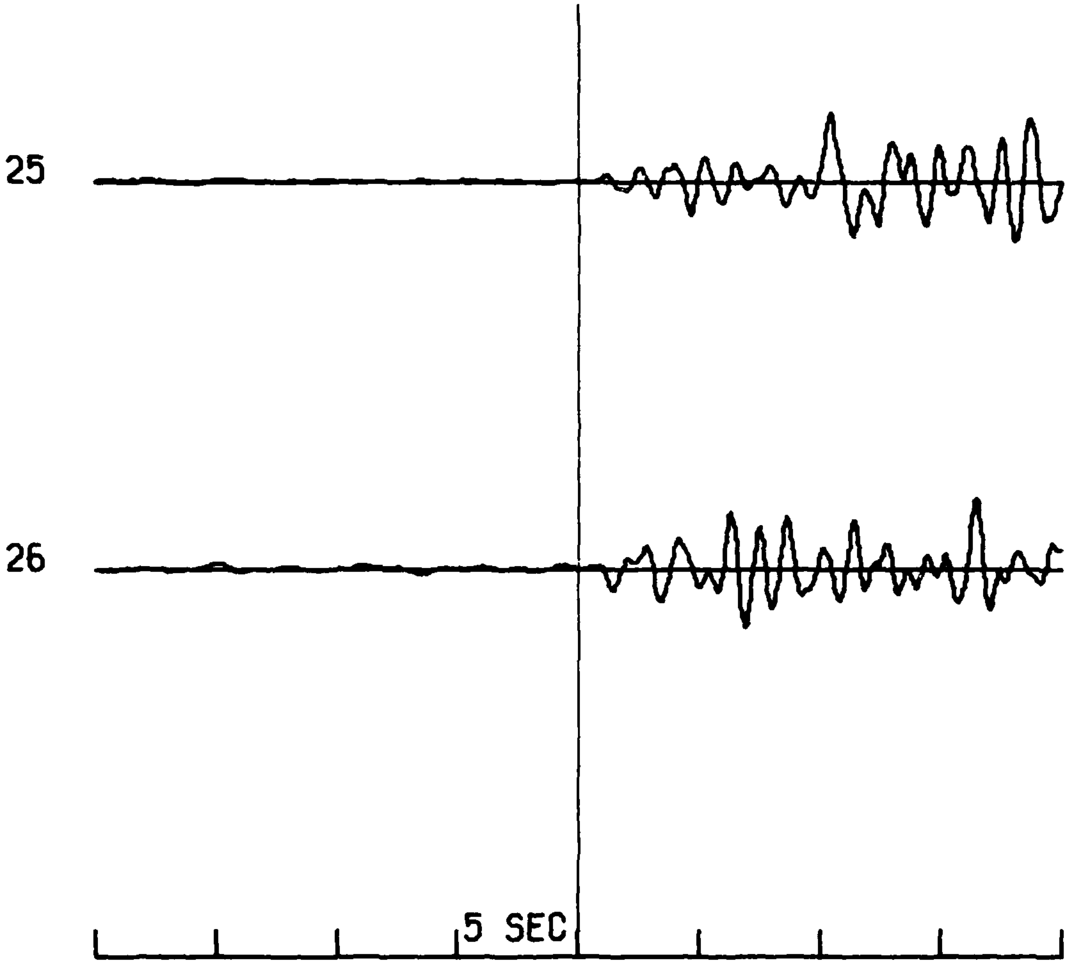
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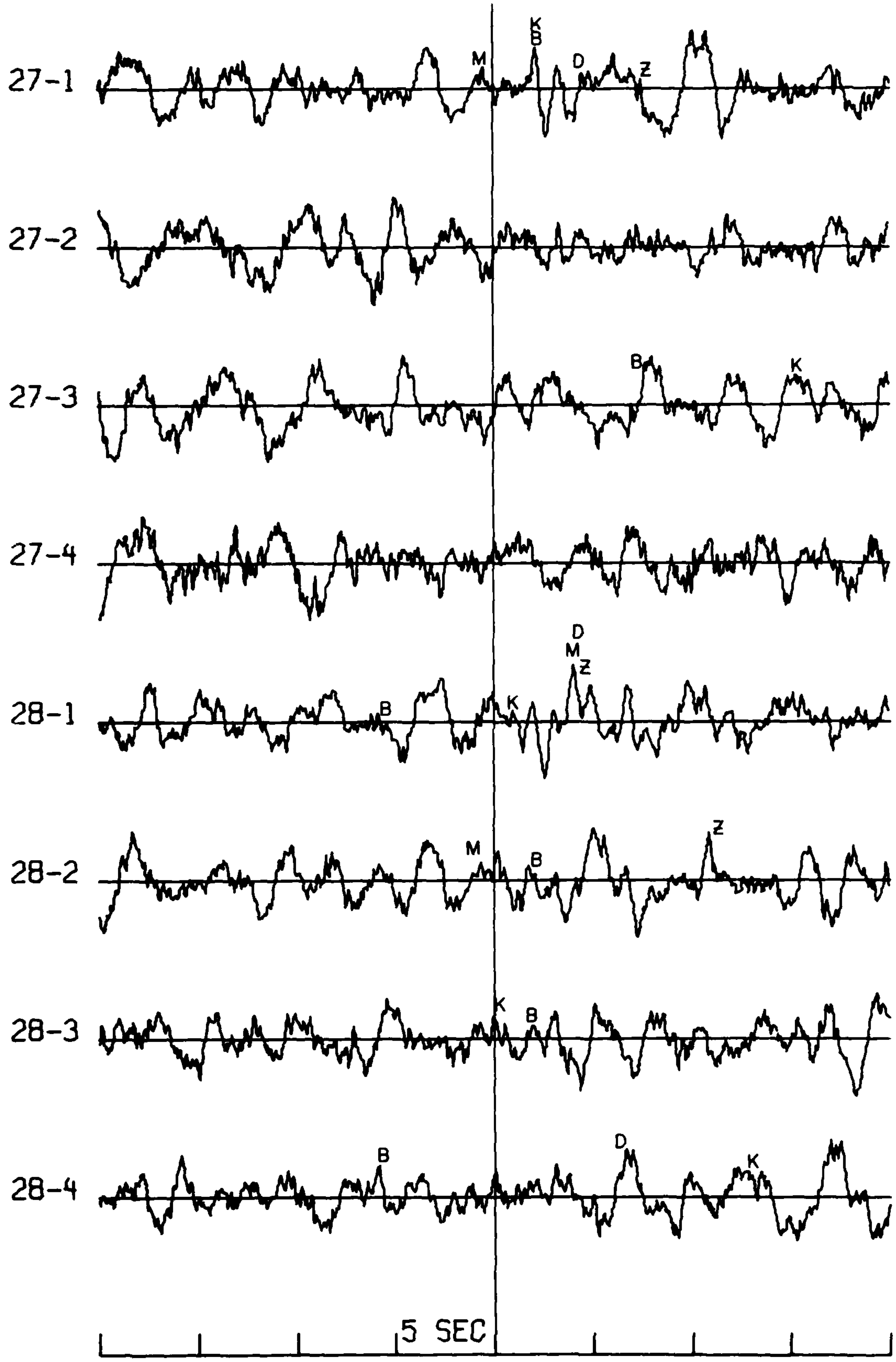
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27-4
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K
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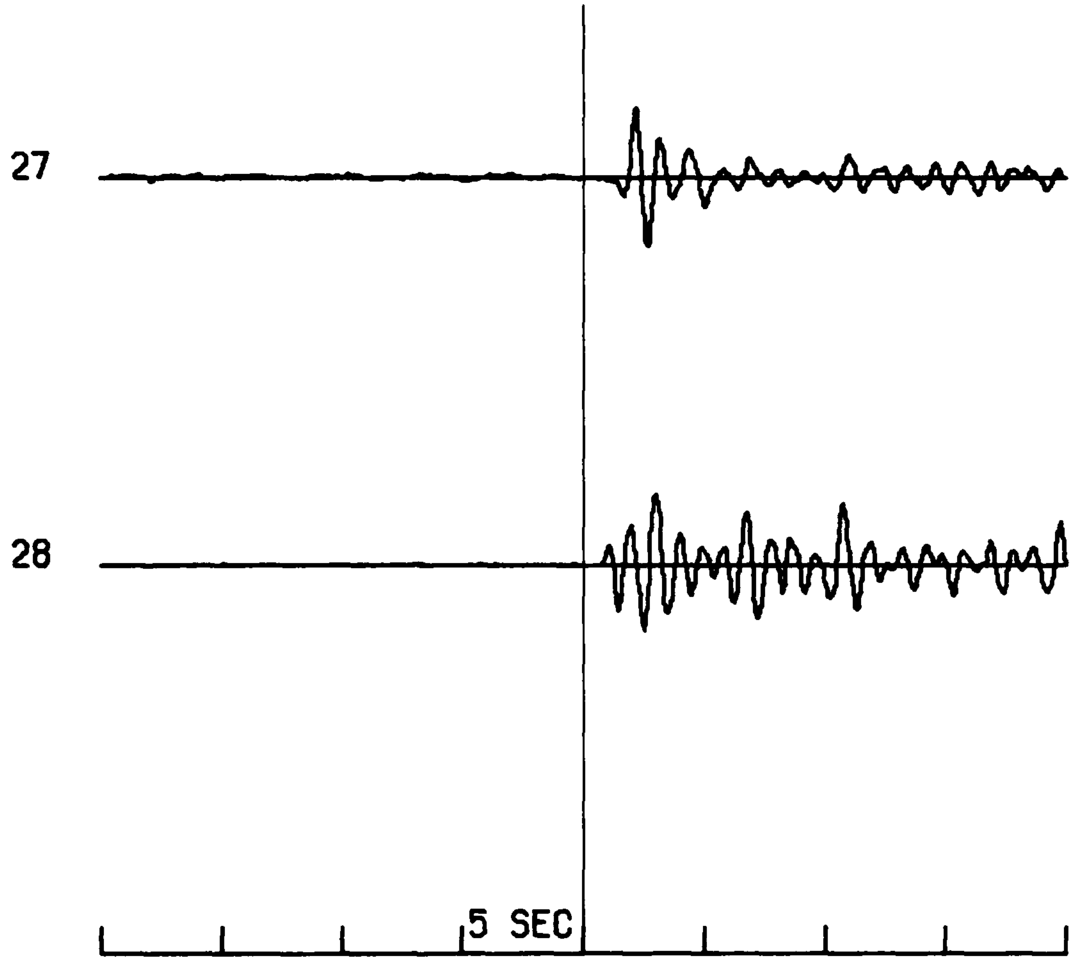
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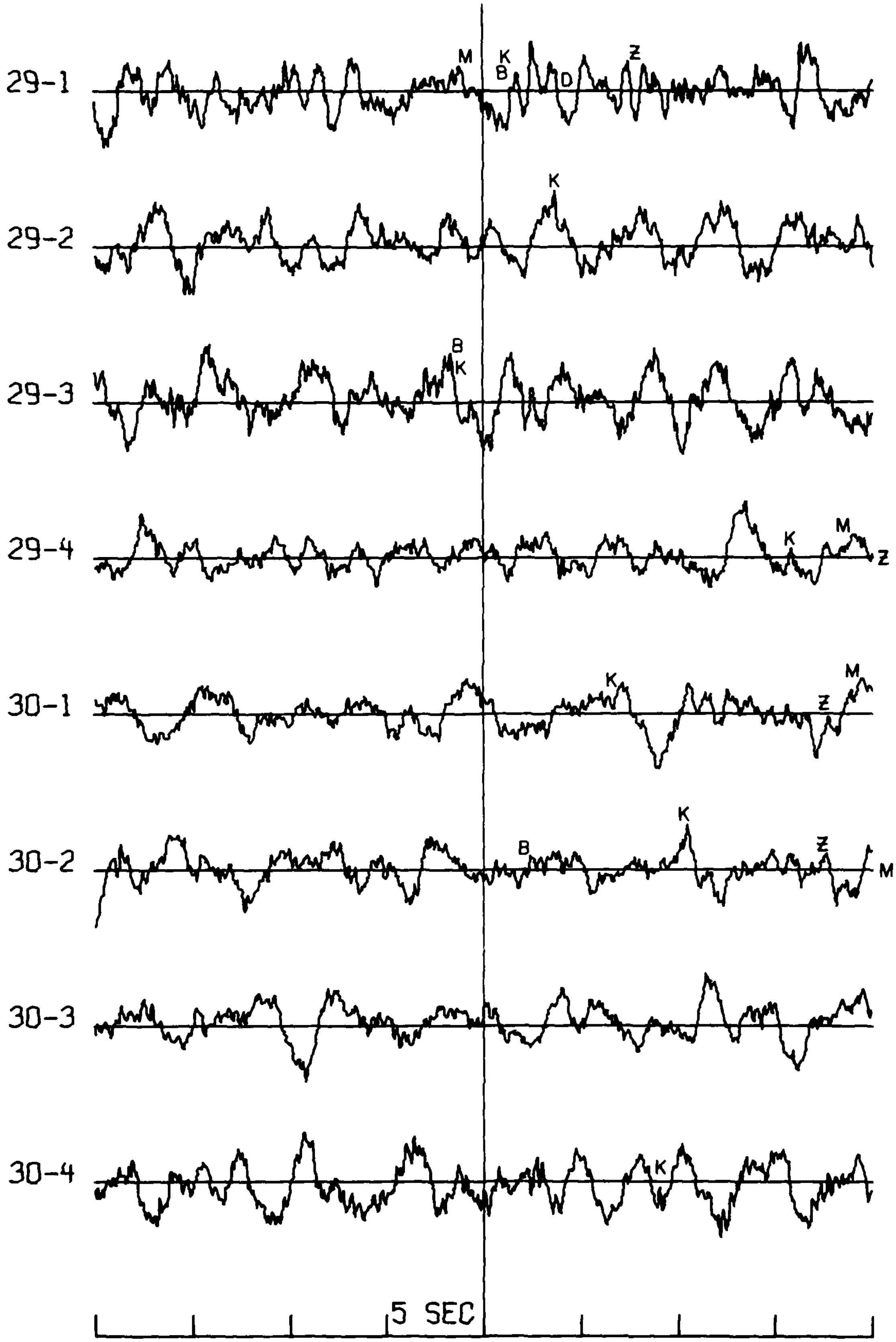
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29-3
B
K
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Z
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B
K
Z
M
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30-4
K
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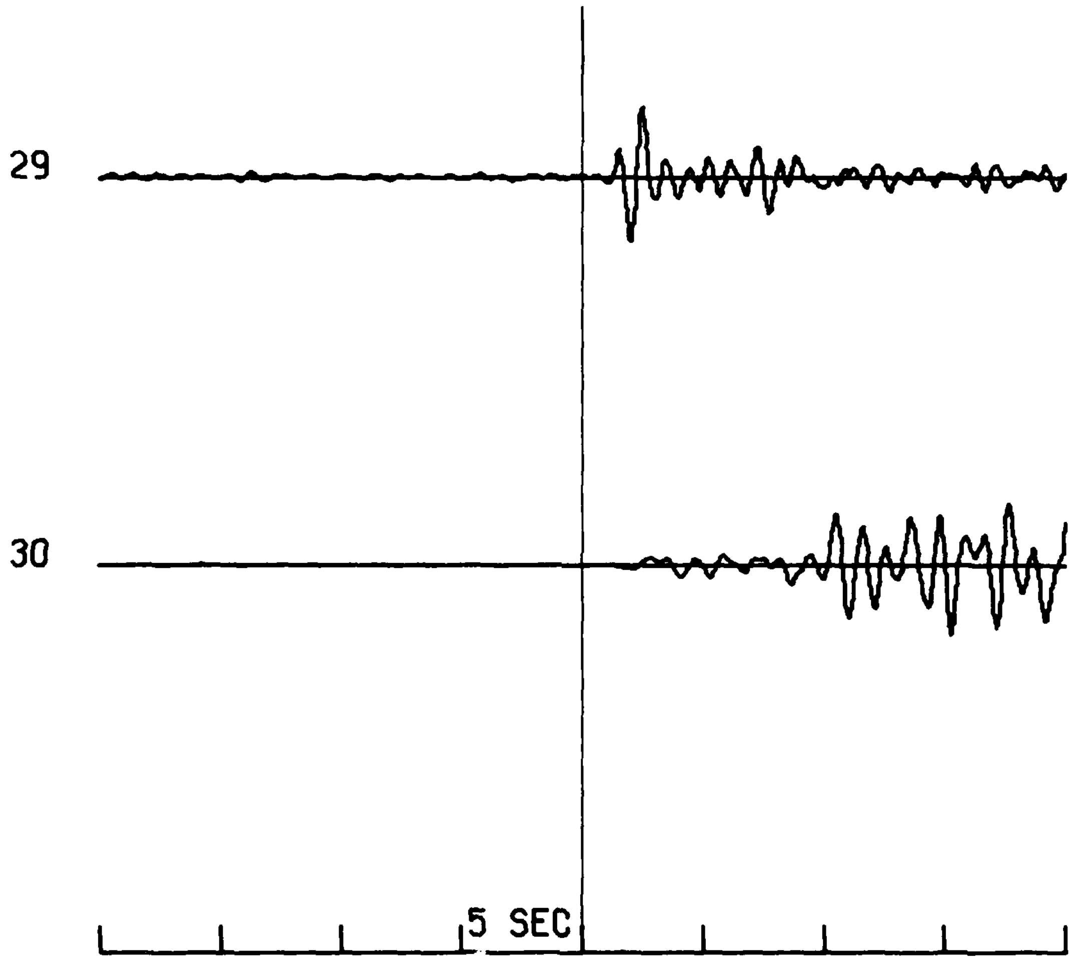
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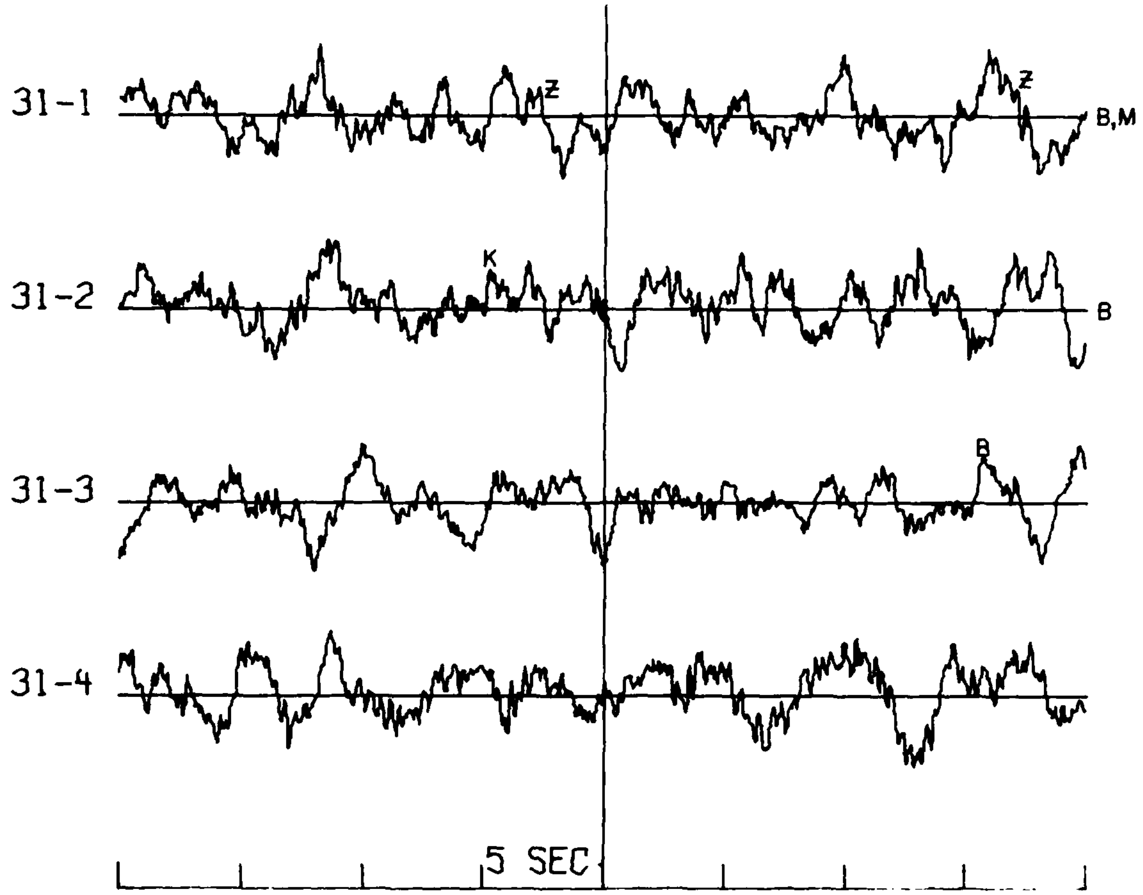
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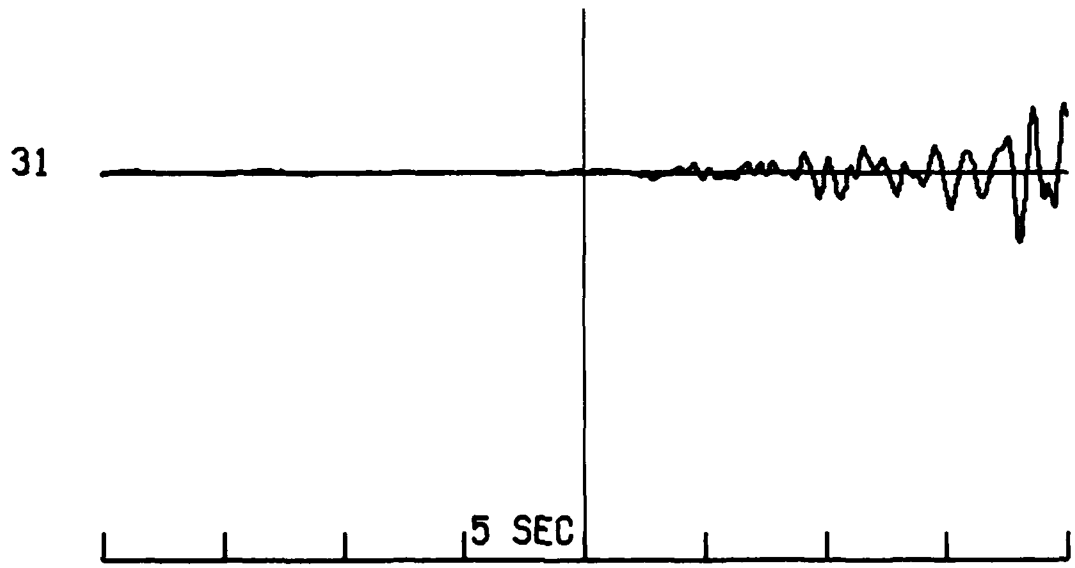
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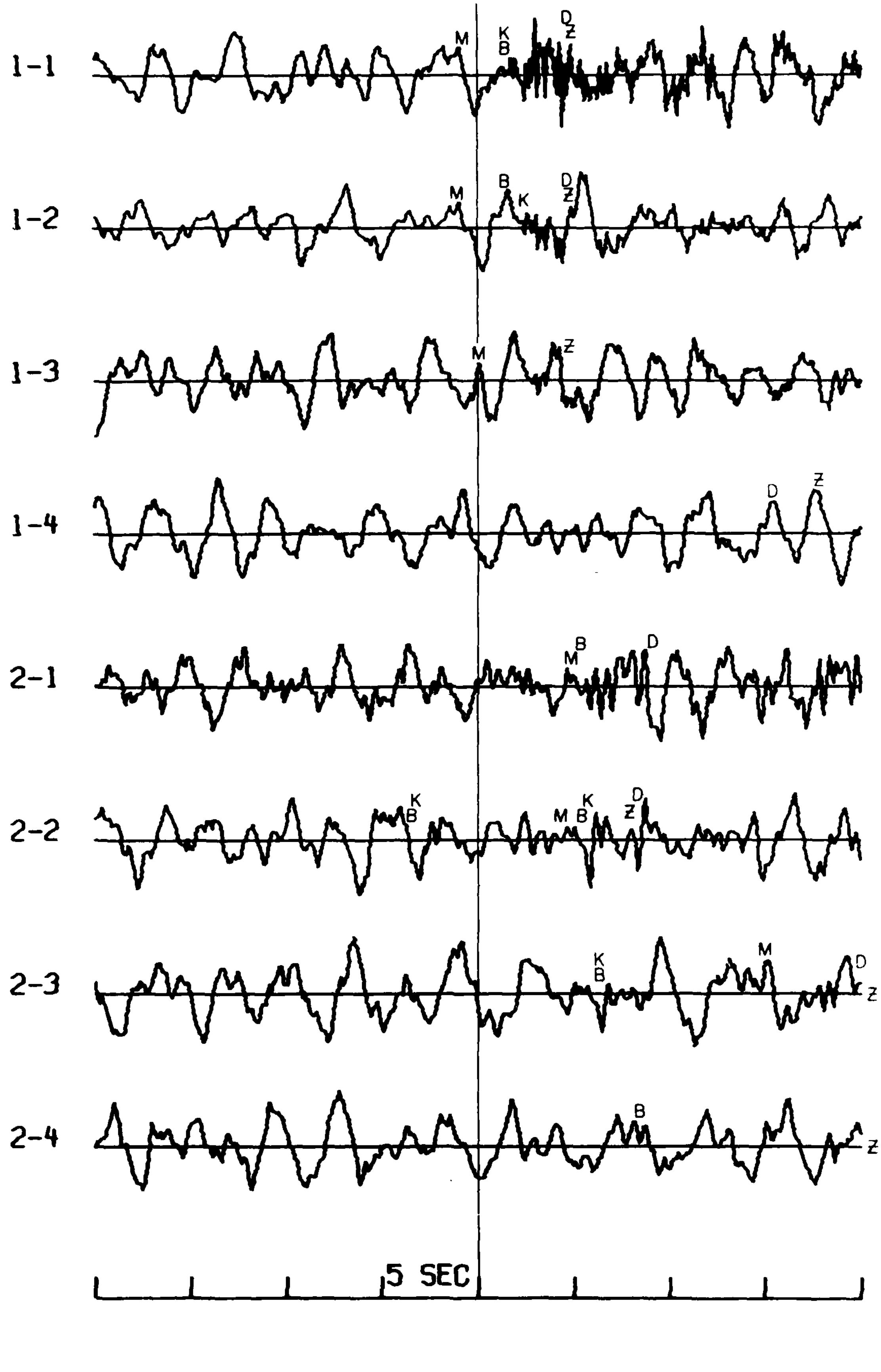
APPENDIX VI

NORSAR Waveform and Detection Markers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2-4
M
K
B
D
Z
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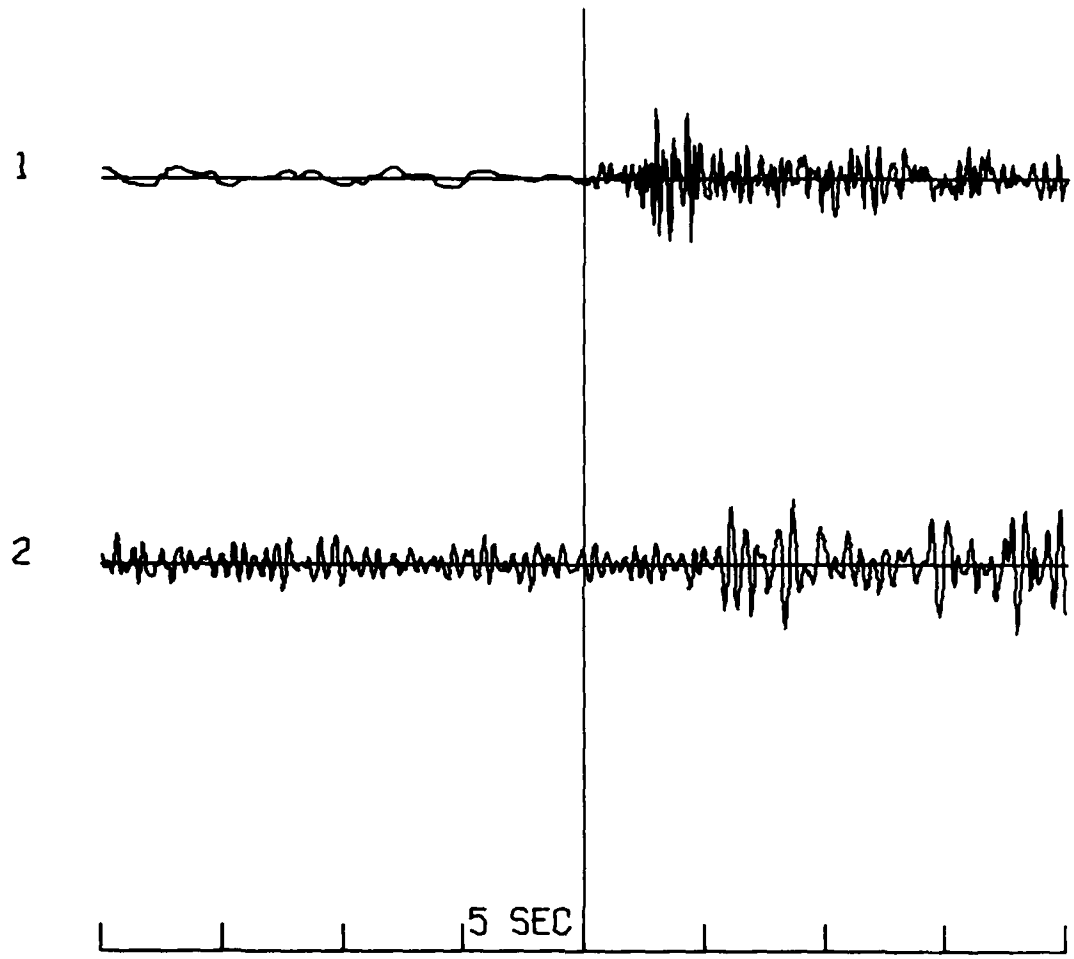
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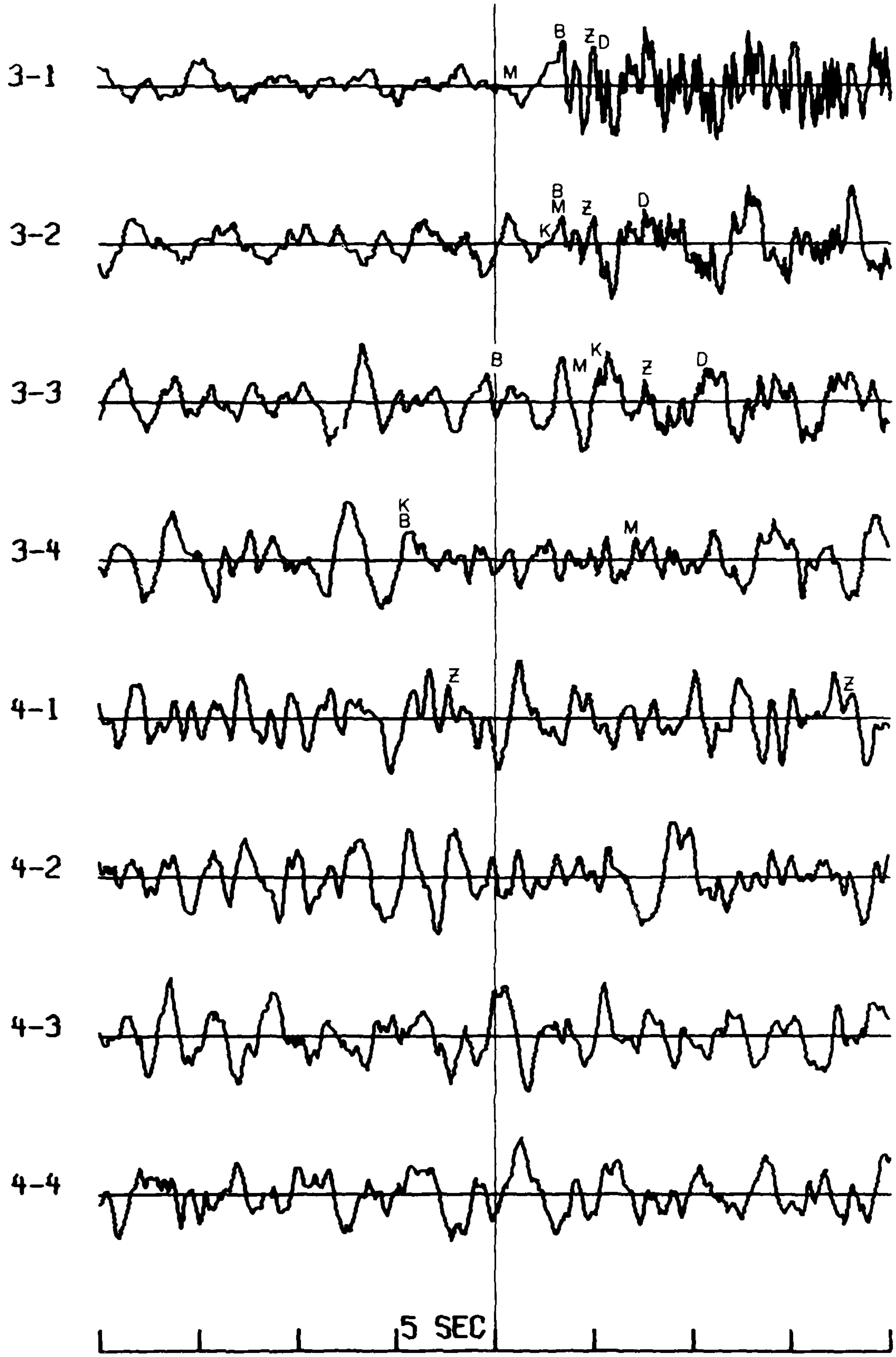
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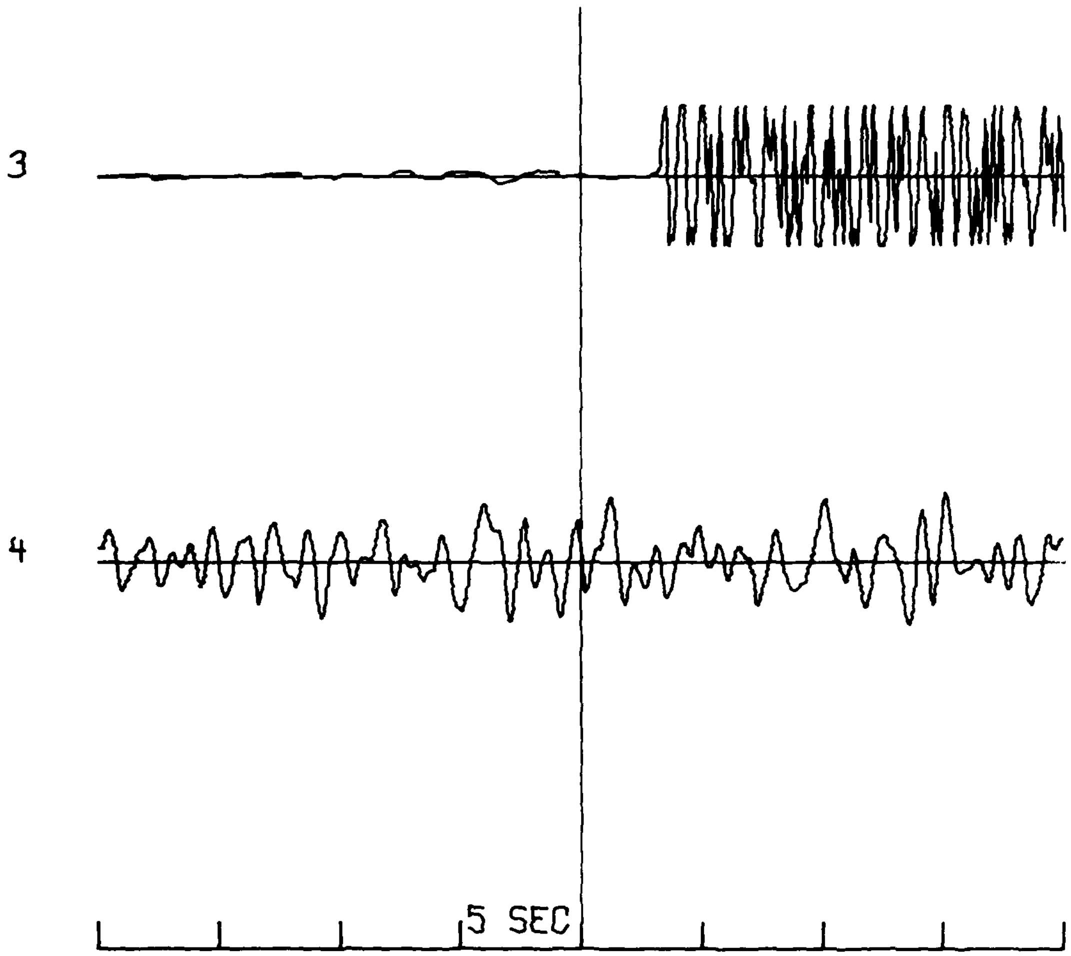
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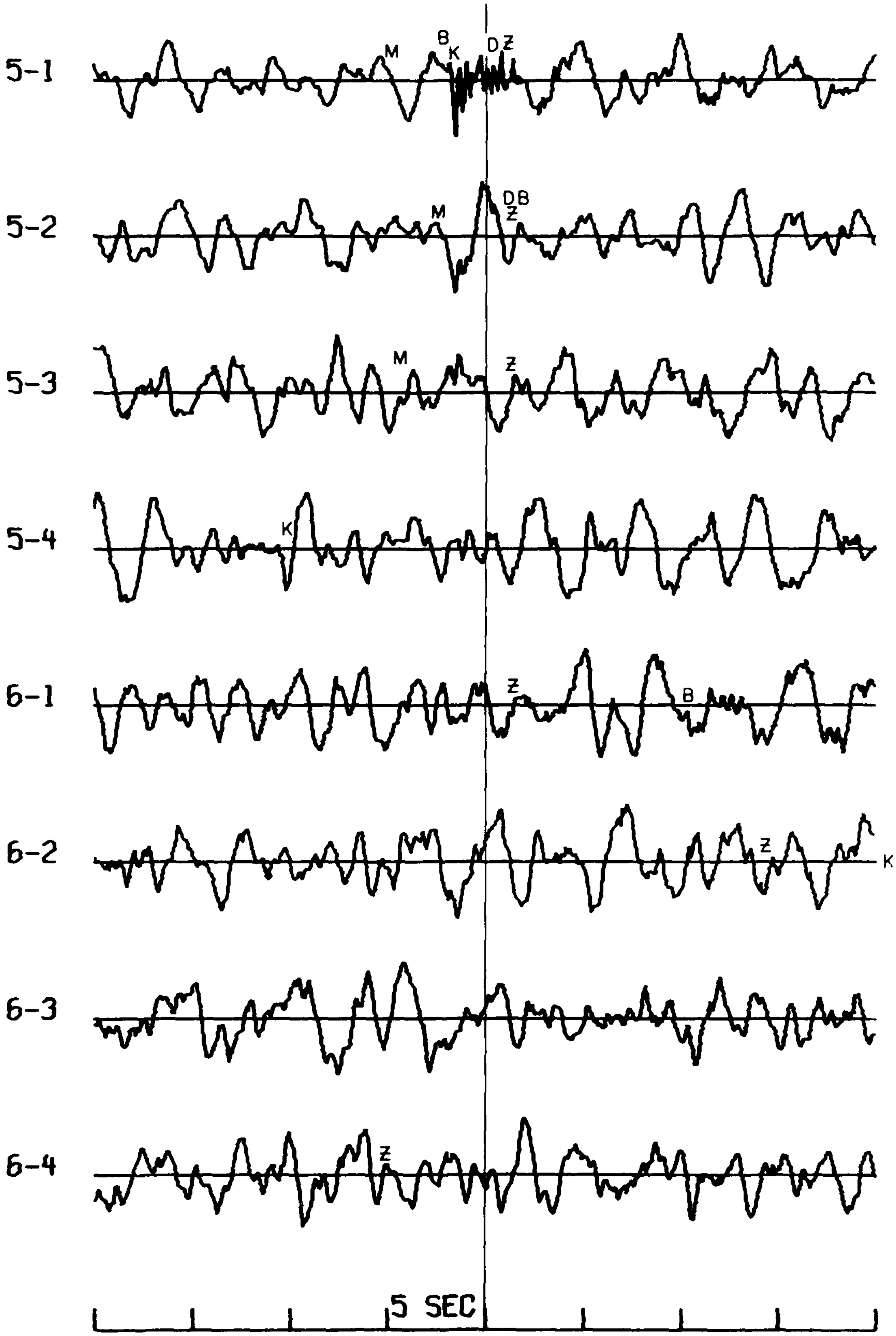
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6-3
6-4
M
B
K
D
Z
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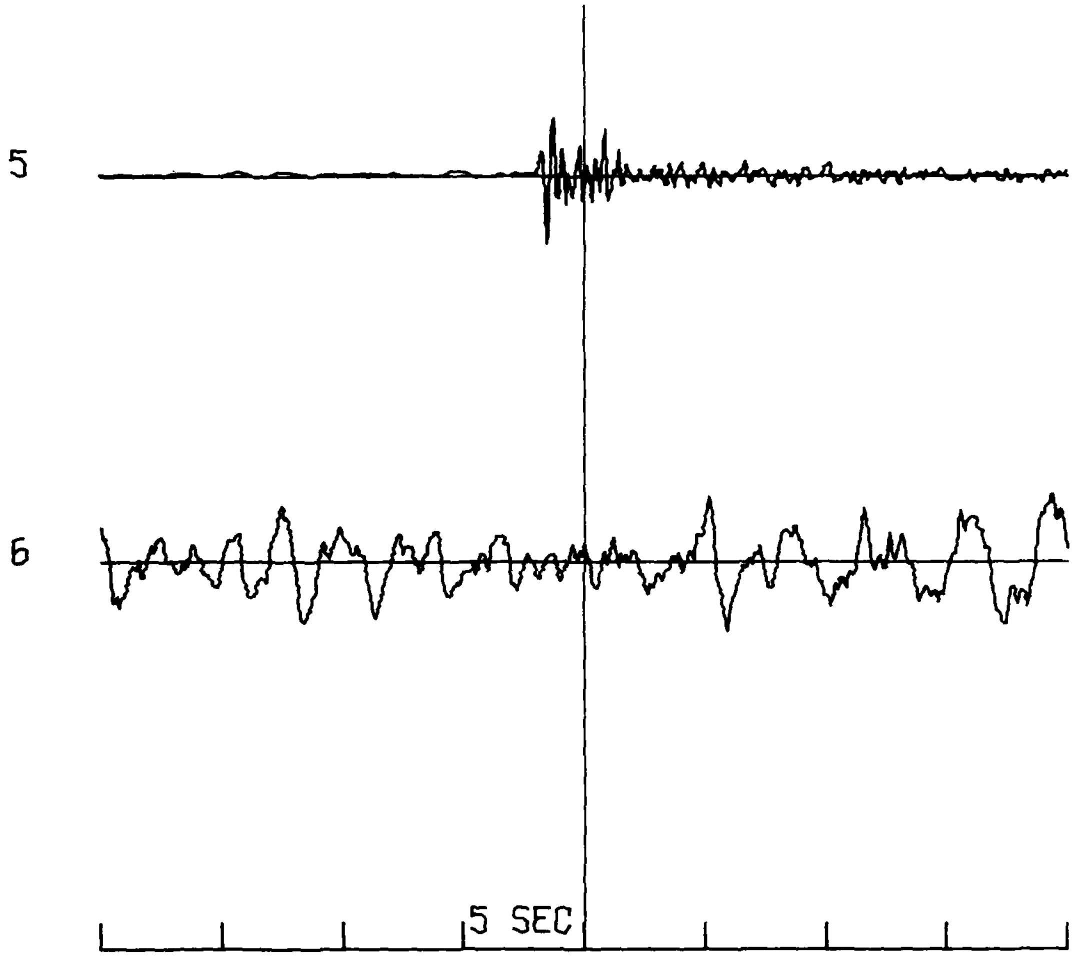
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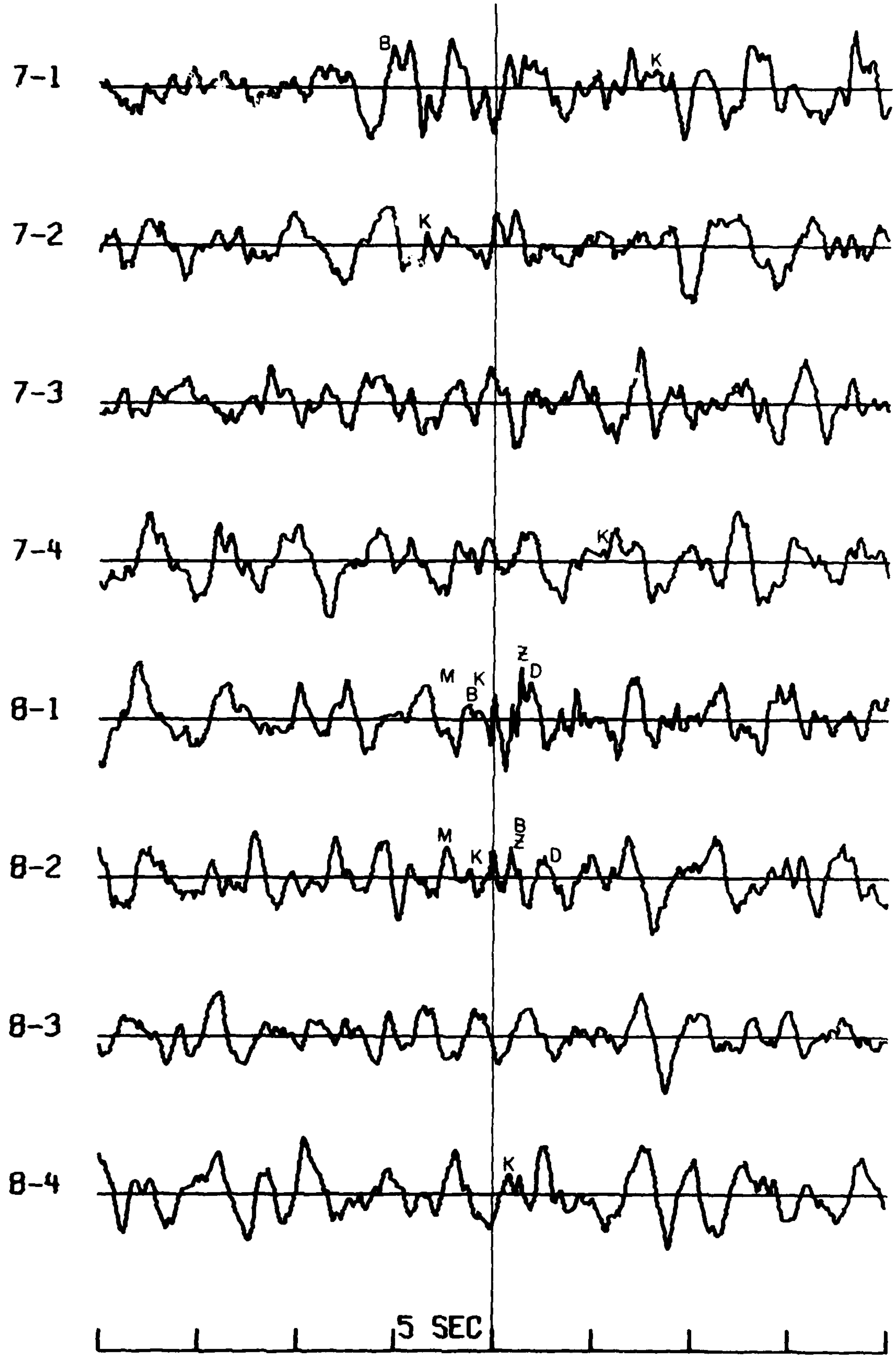

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B
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M
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B
Z
D
8-3
8-4
K
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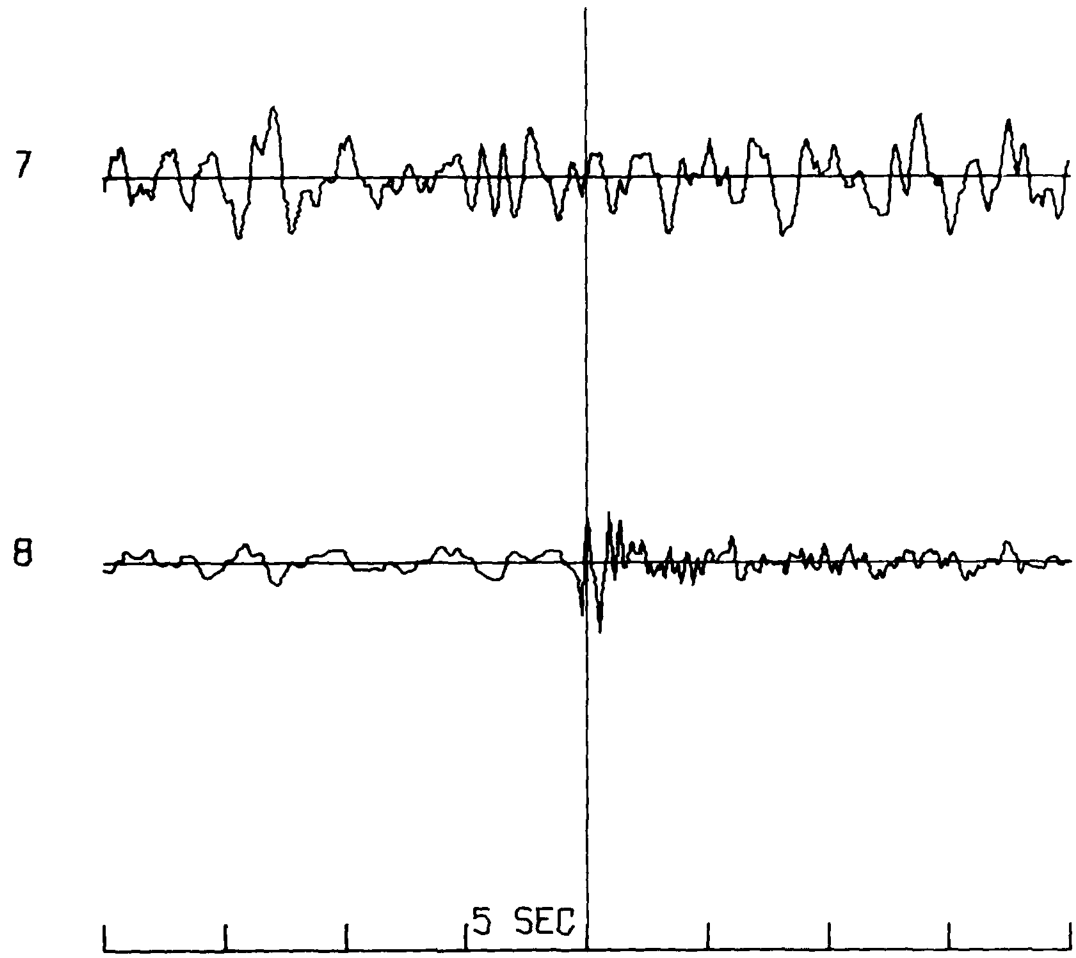
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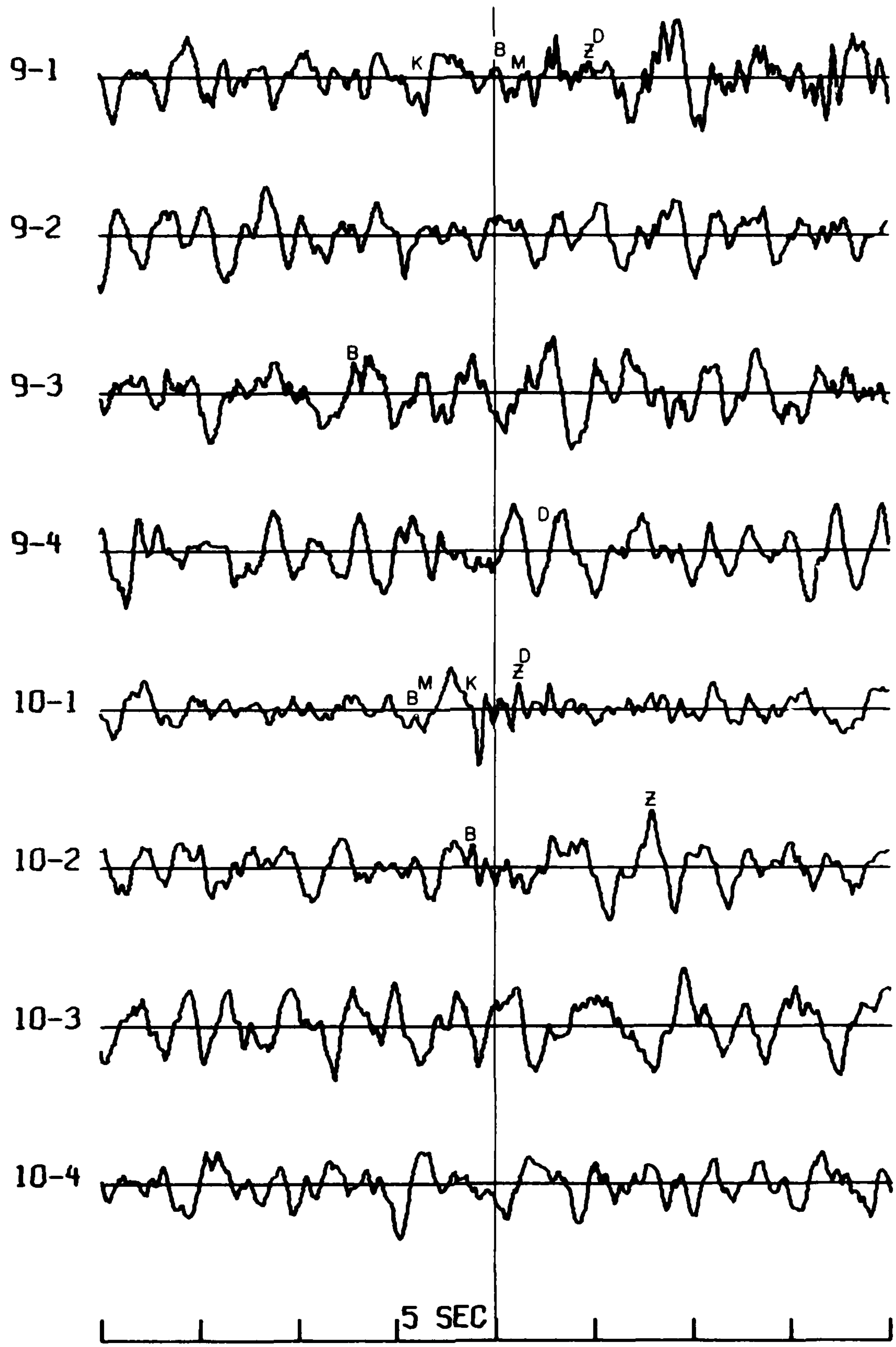
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10-4
K
B
M
Z
D
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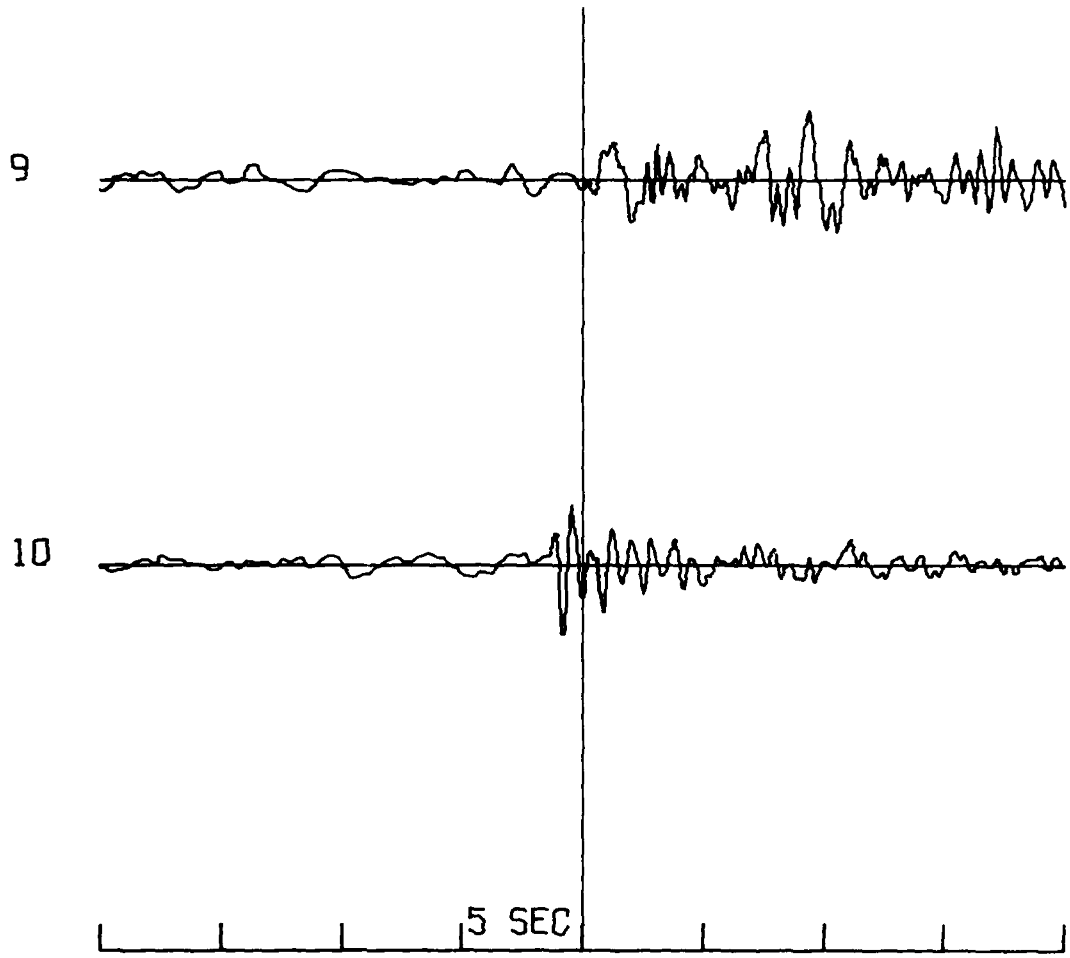

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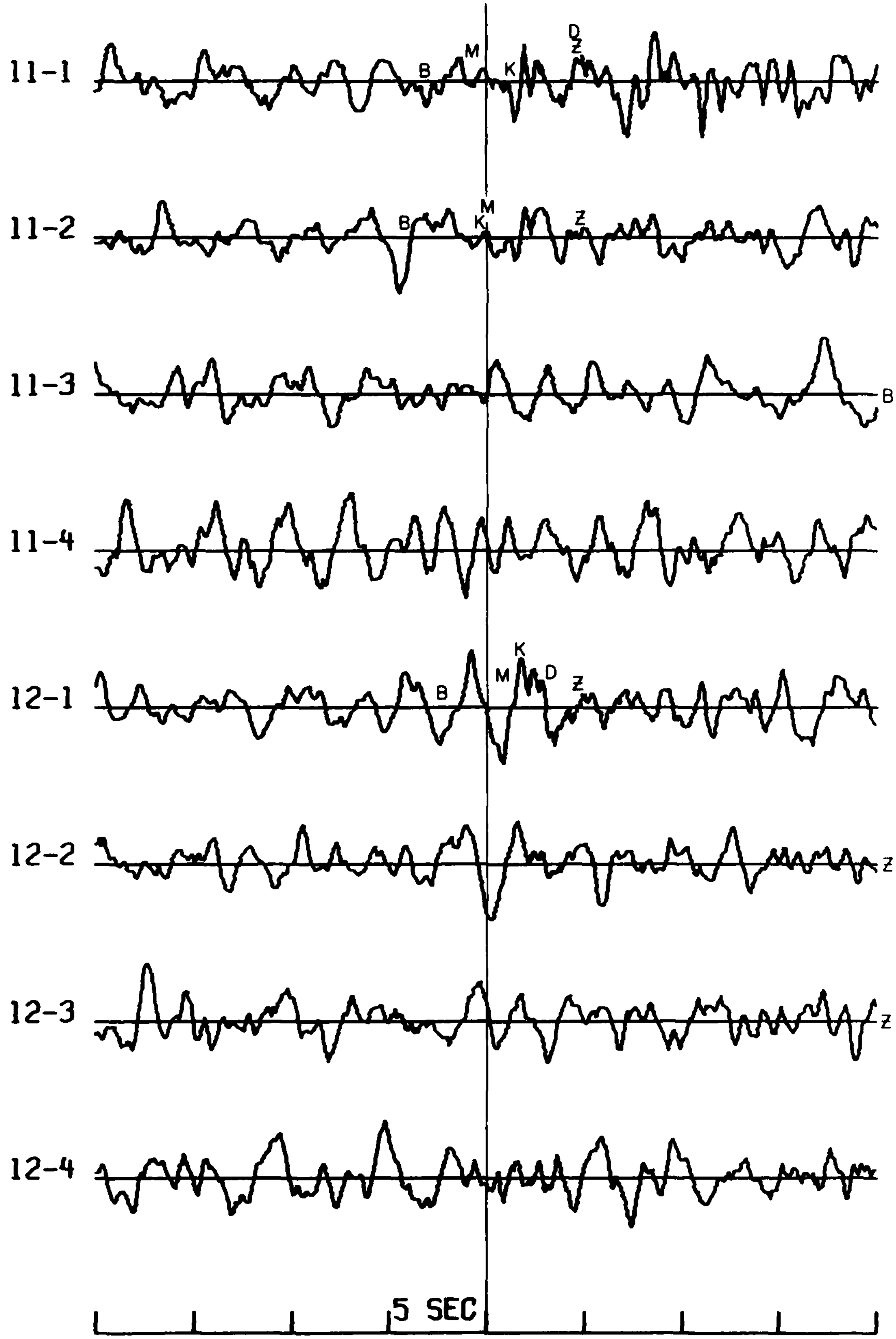
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B
M
K
D
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Z
12-4
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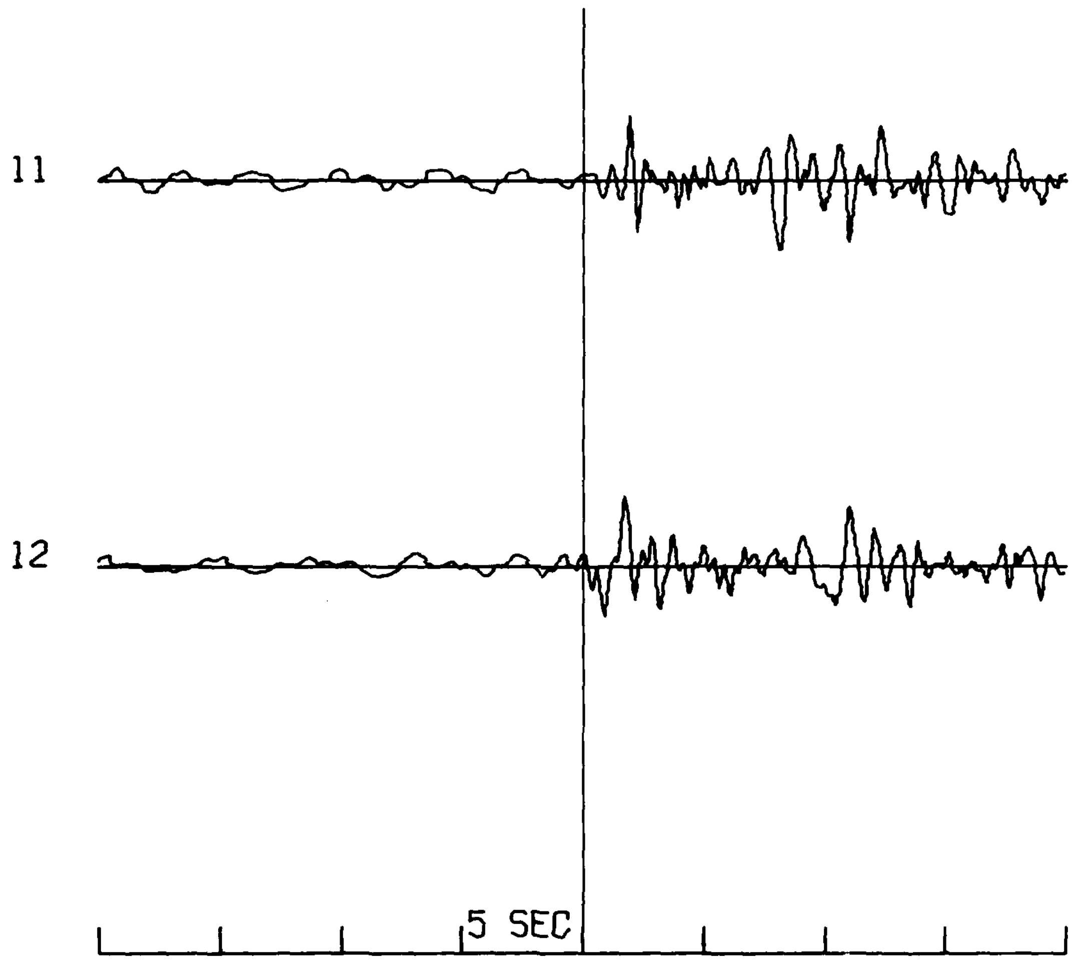
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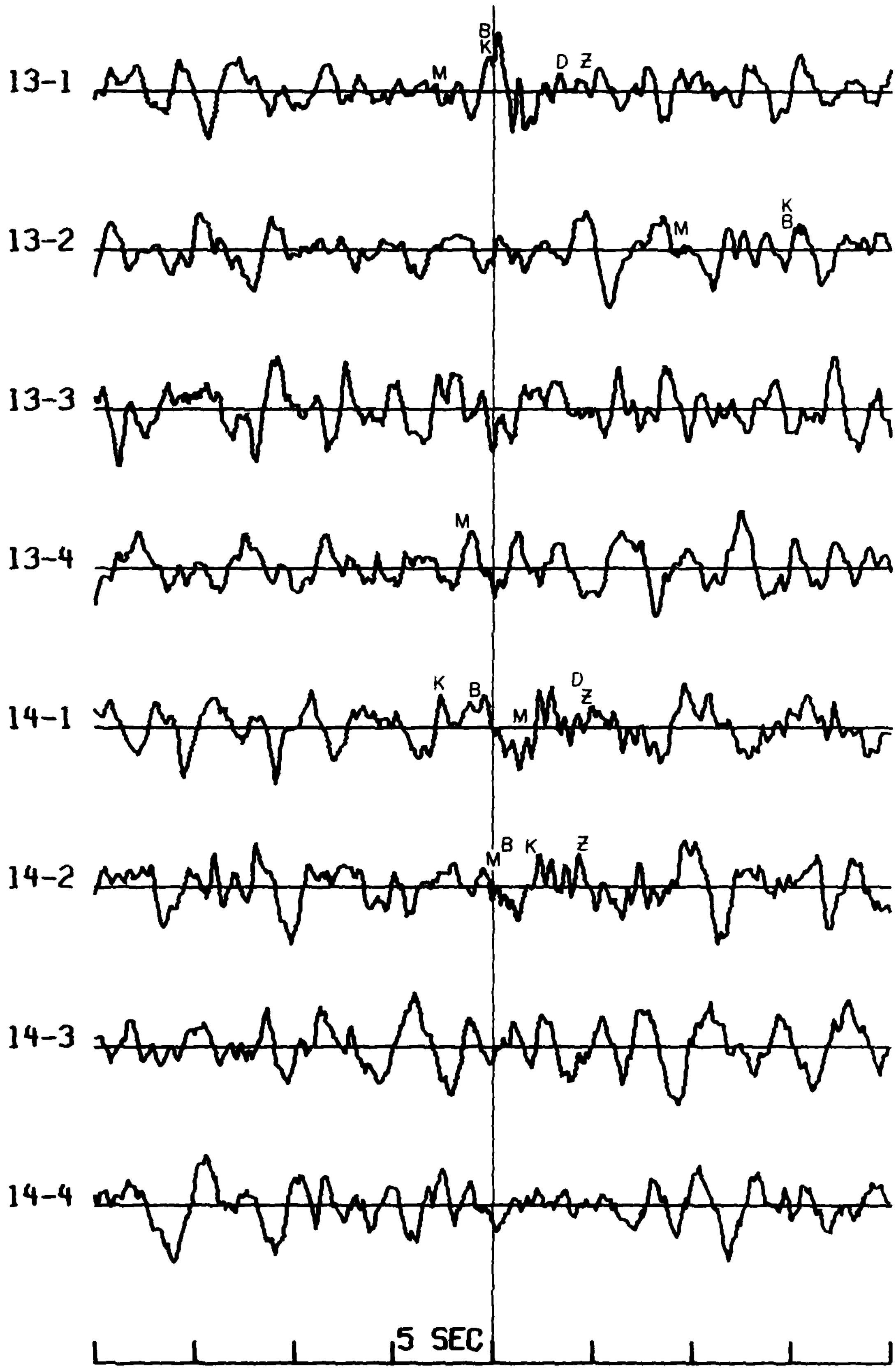
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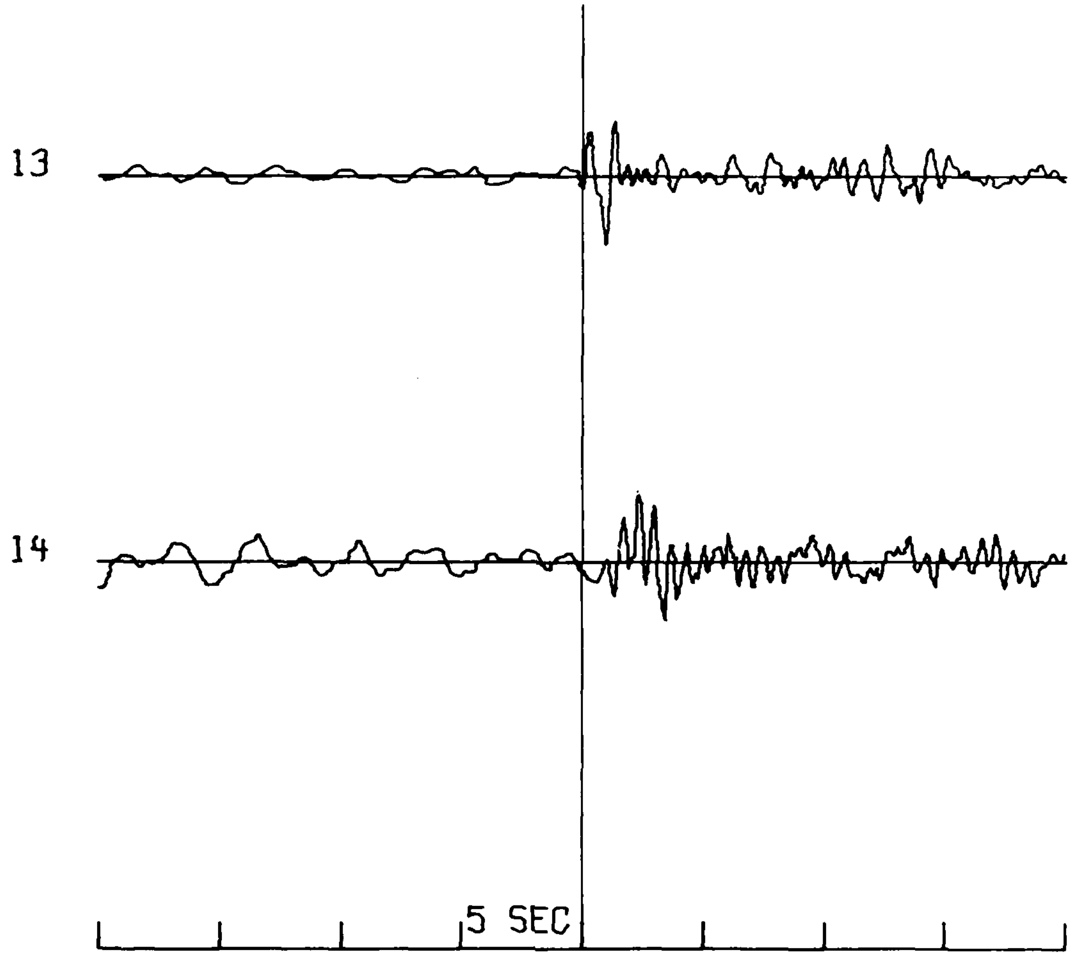
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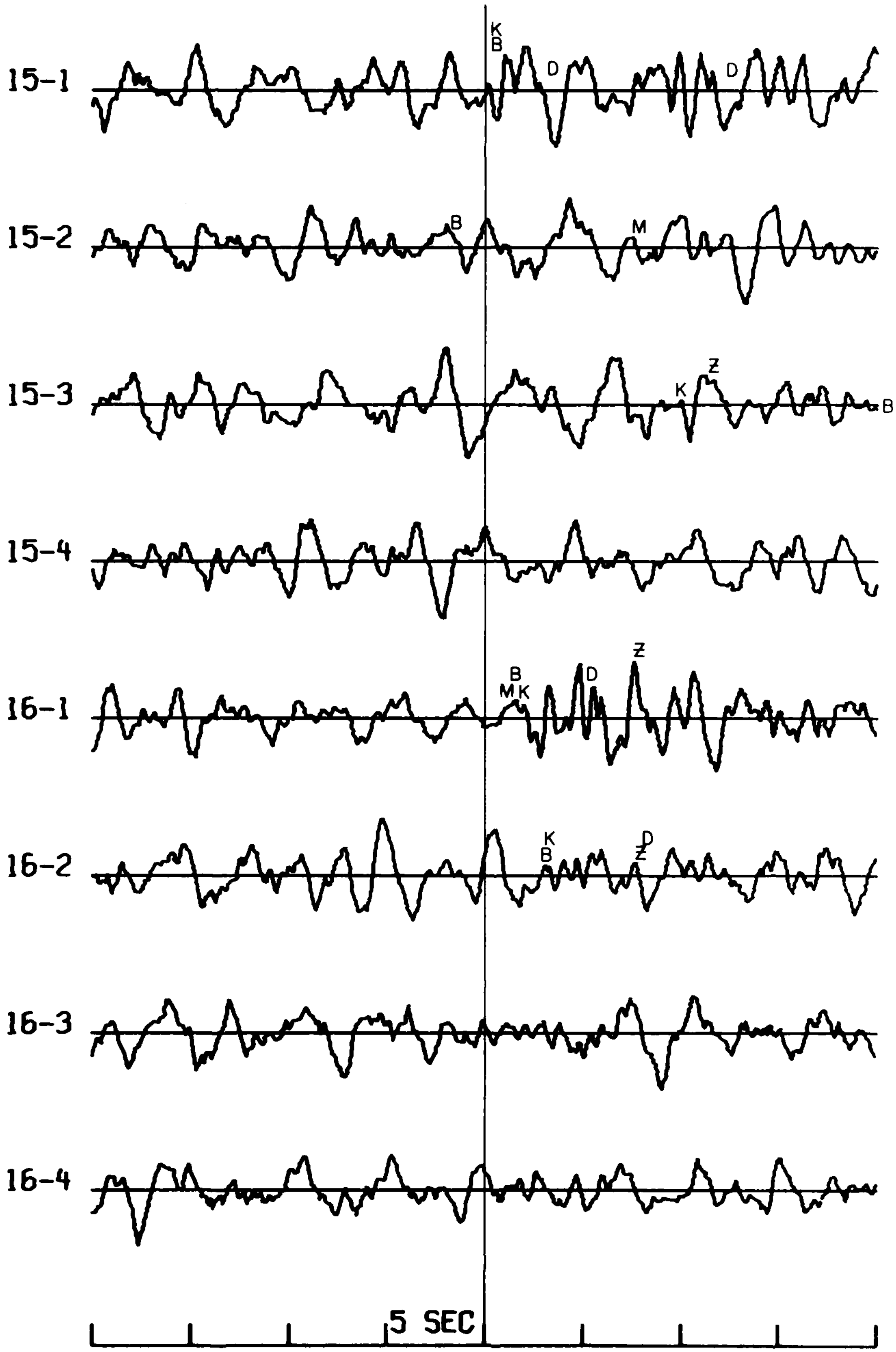
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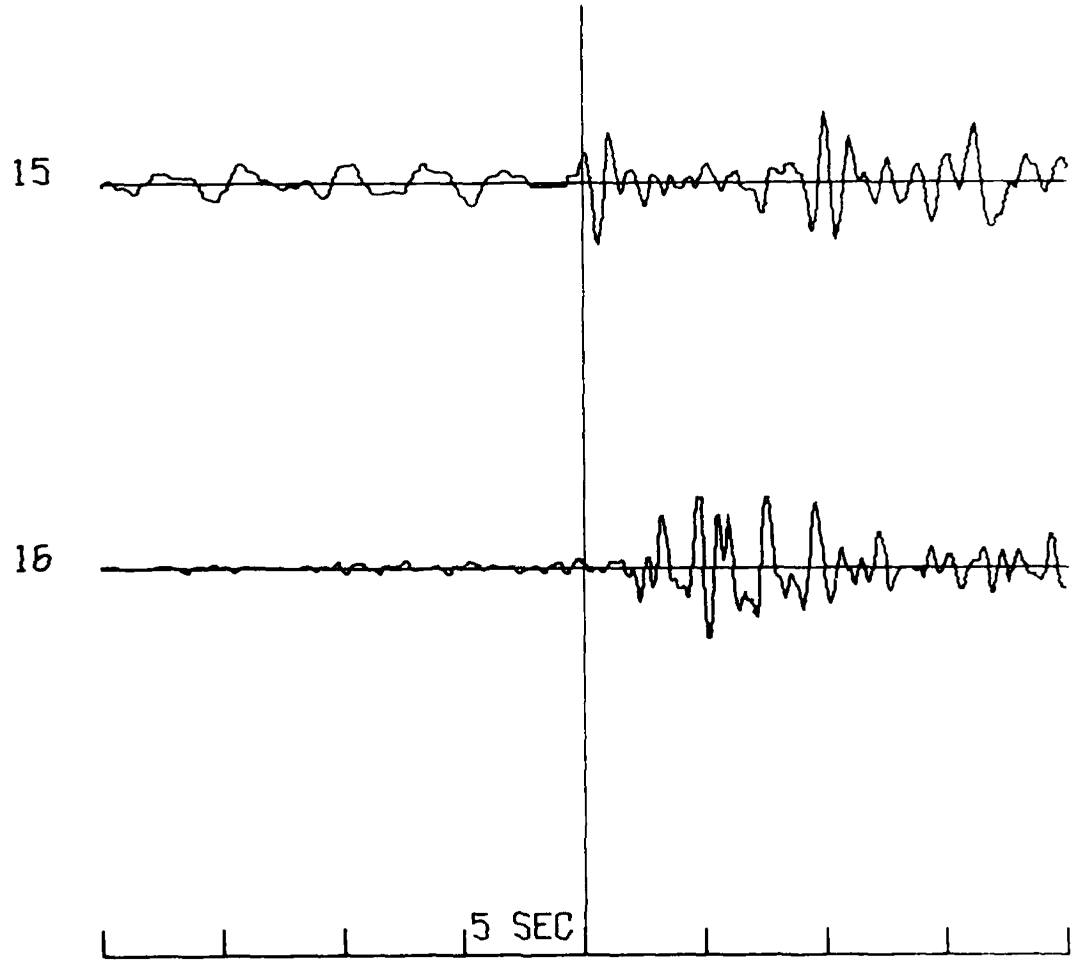
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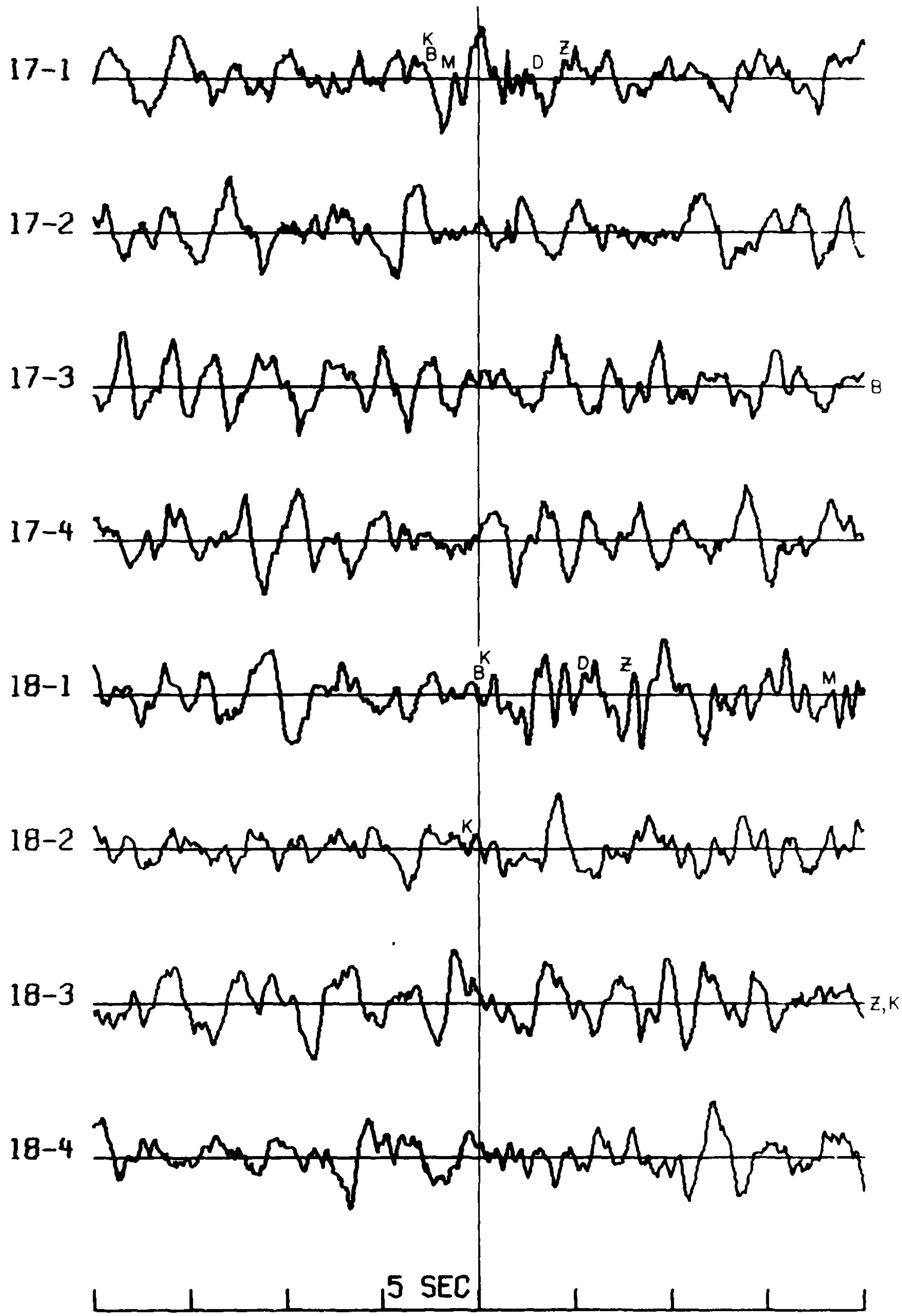
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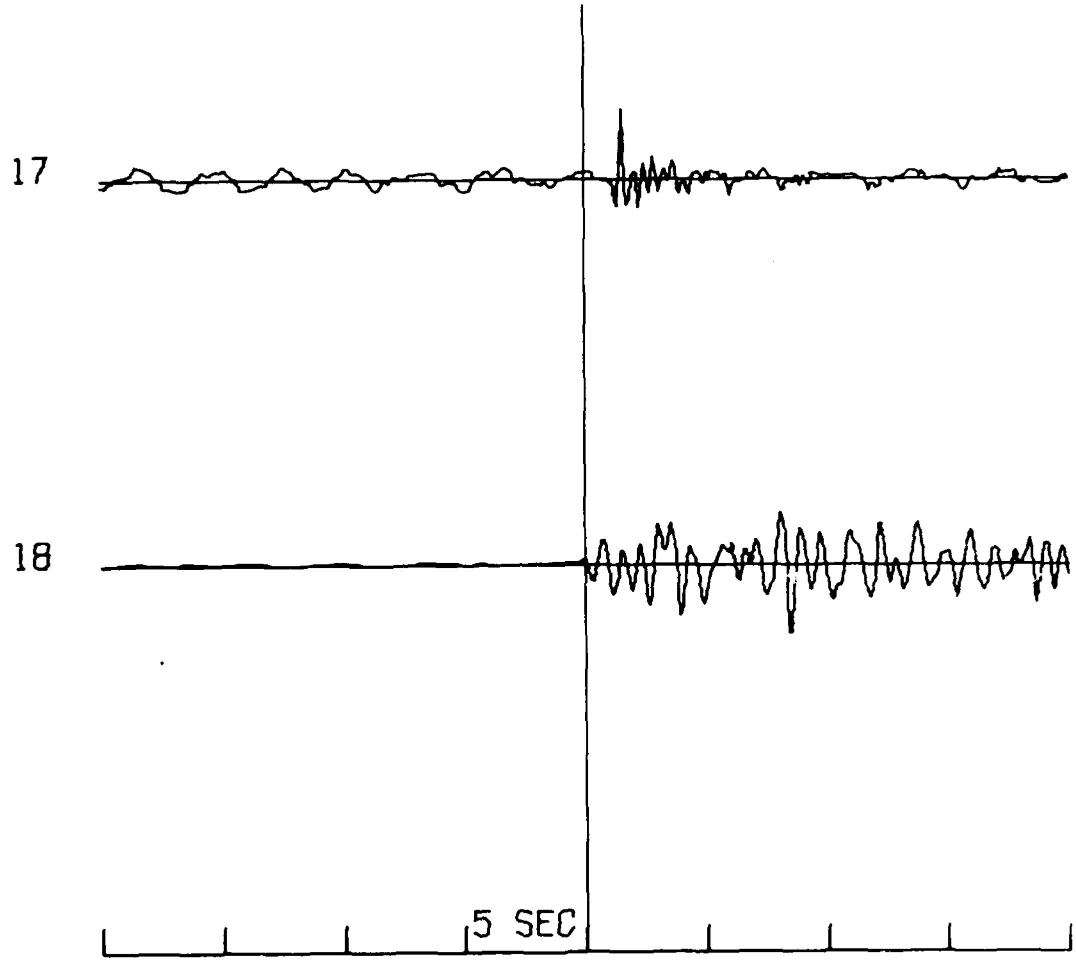
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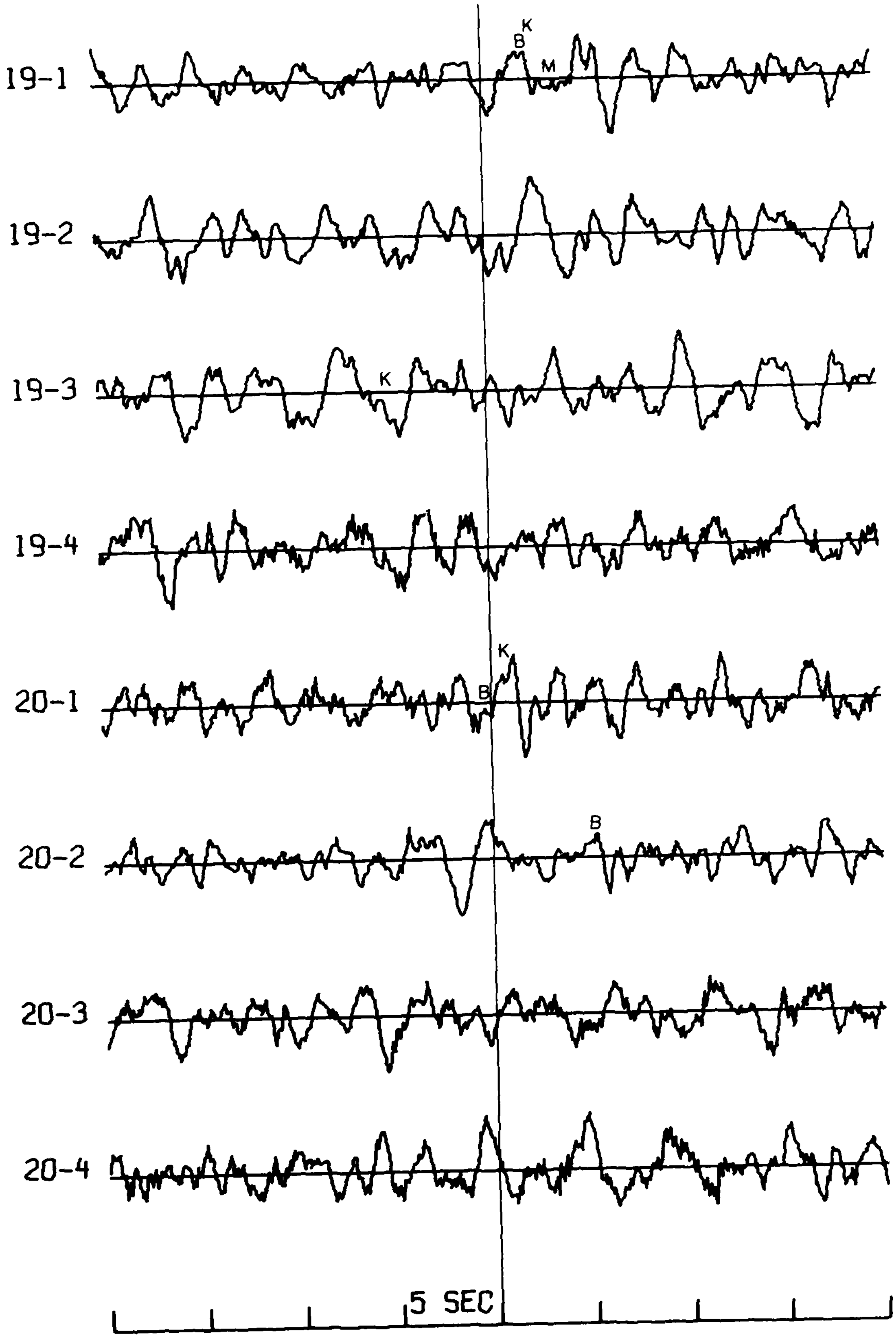
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K
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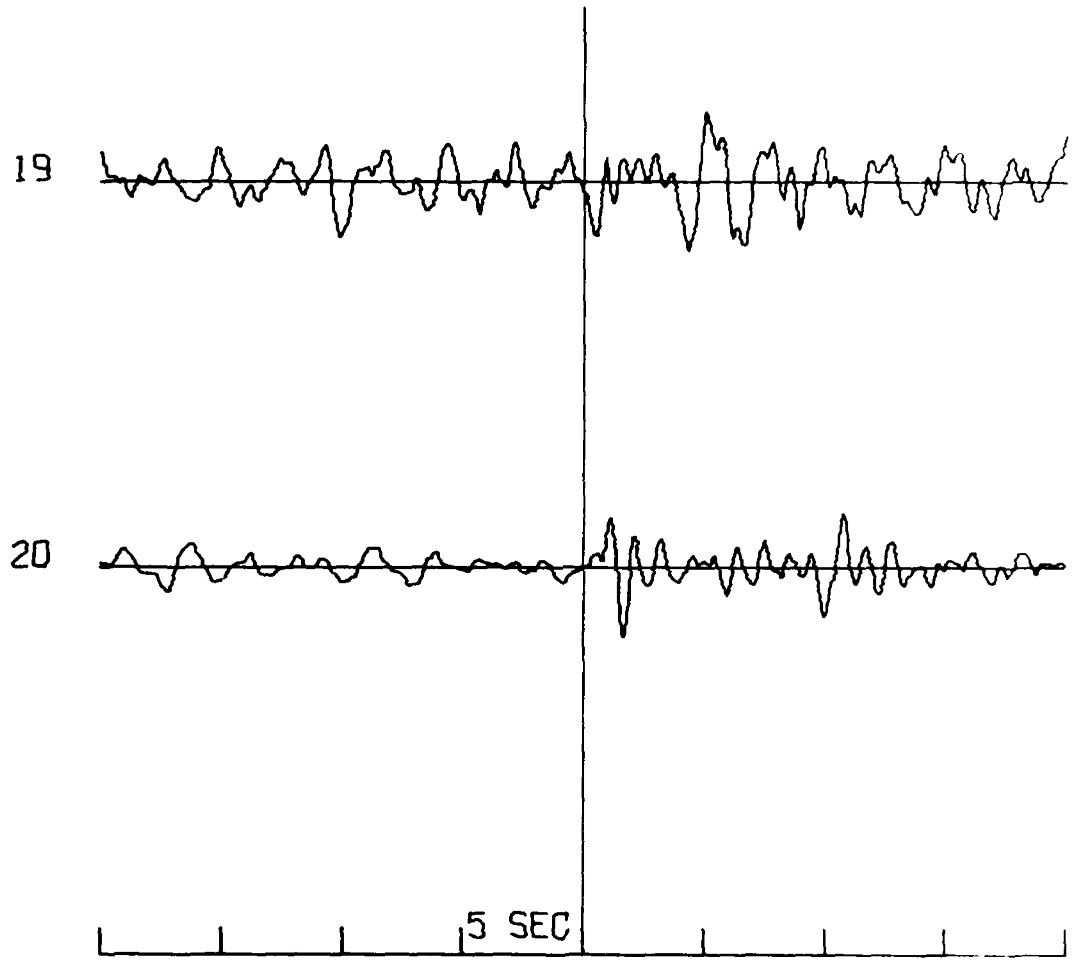
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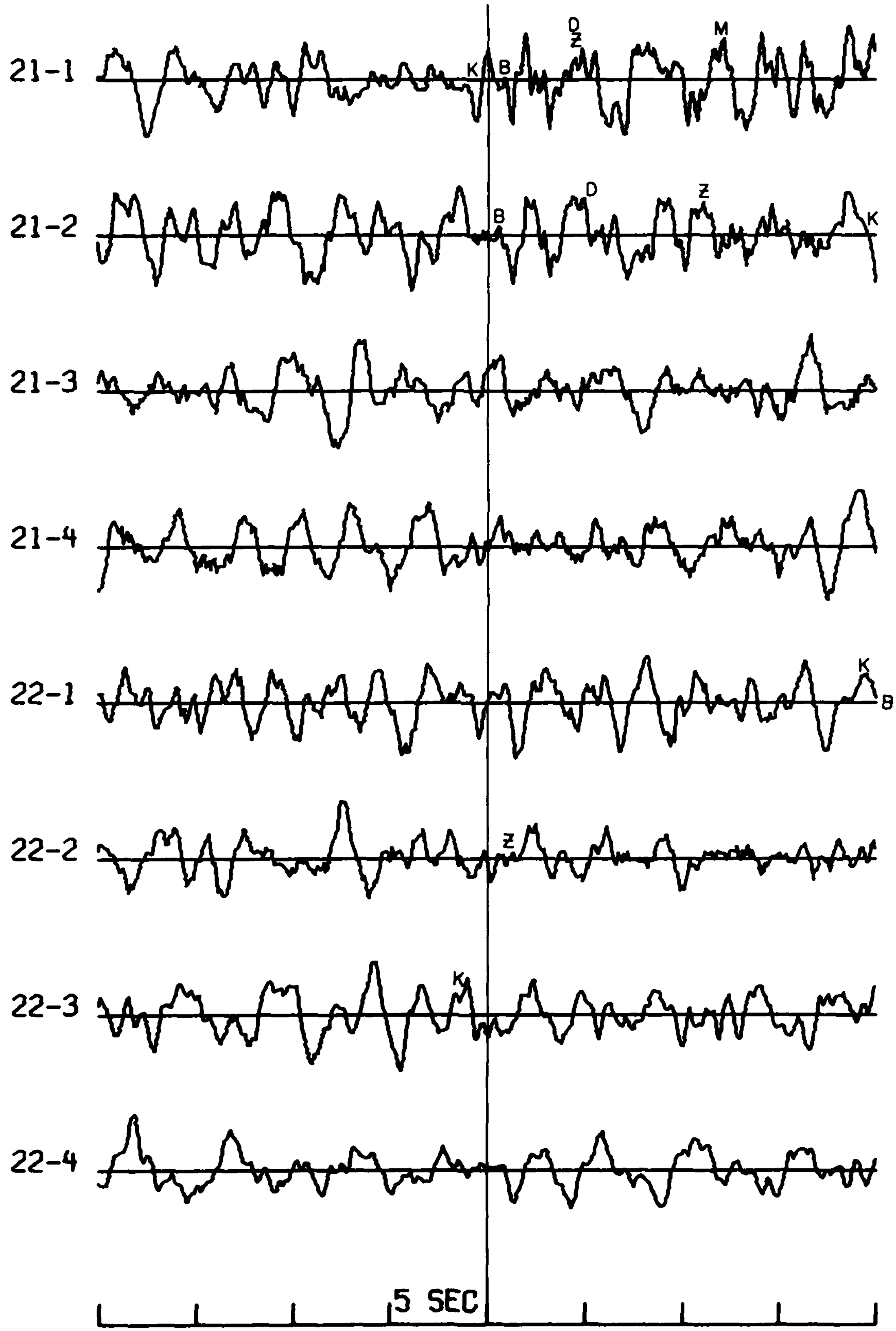
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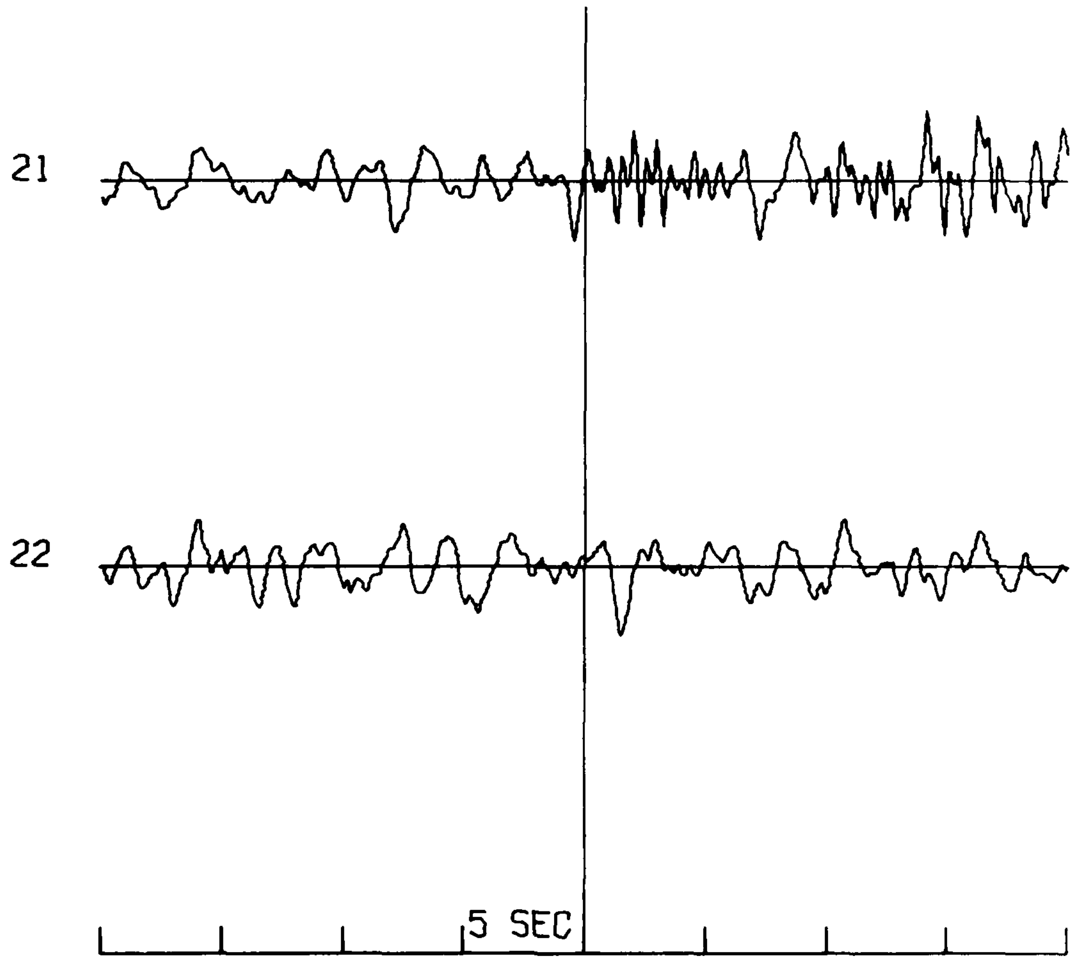
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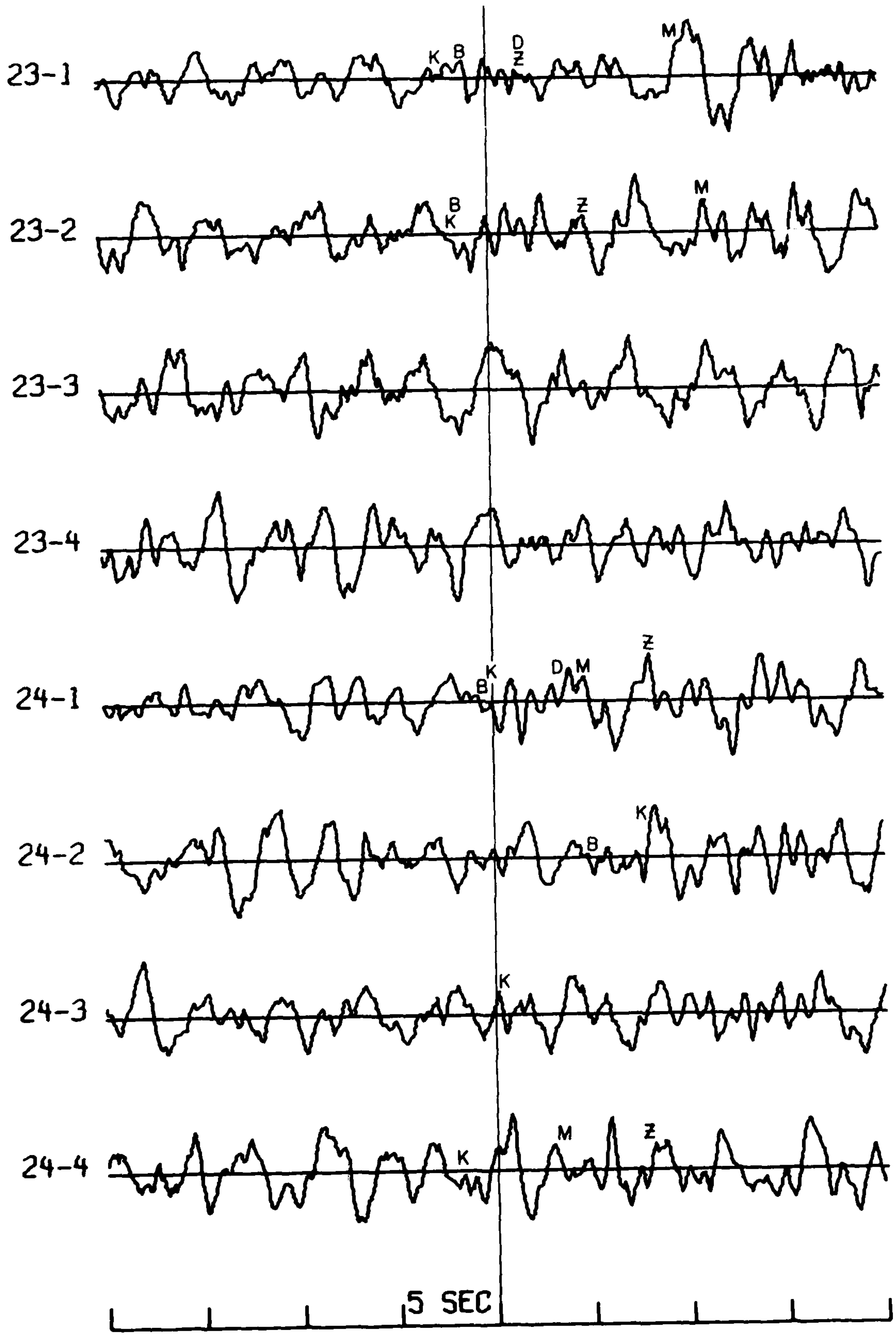
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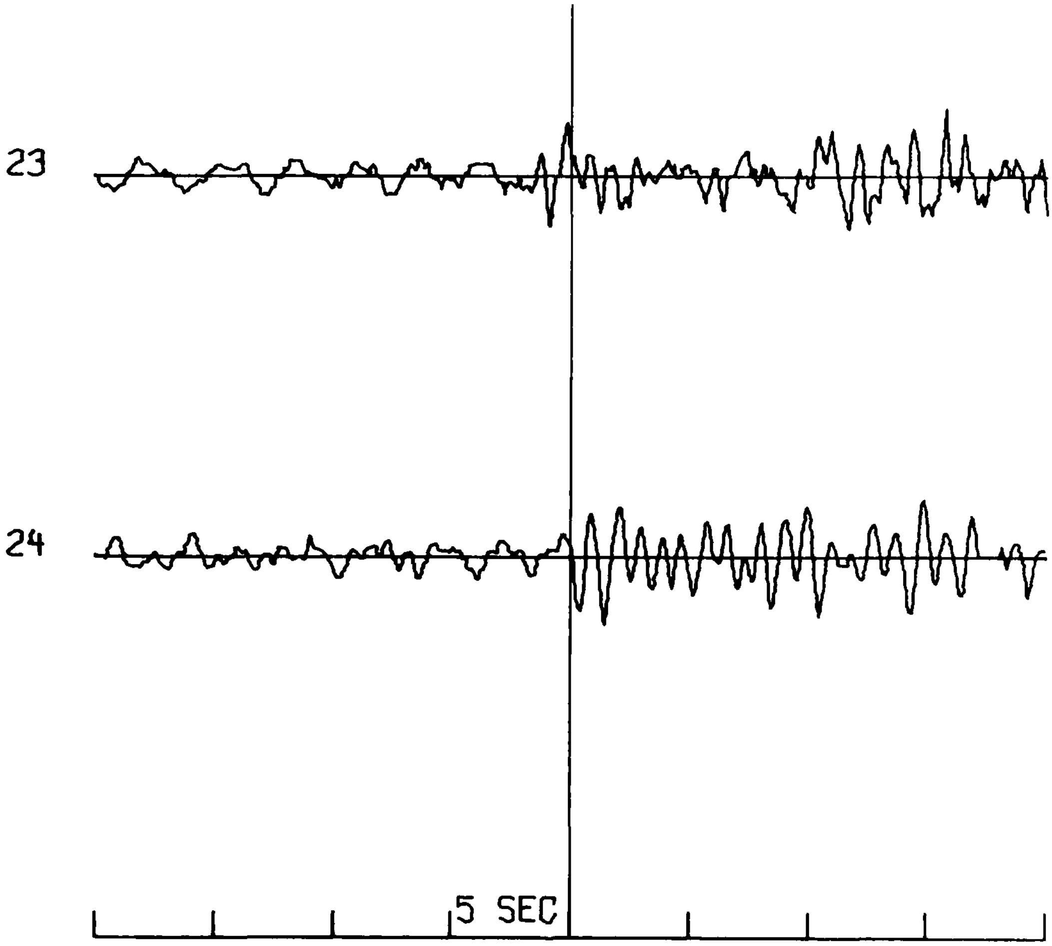
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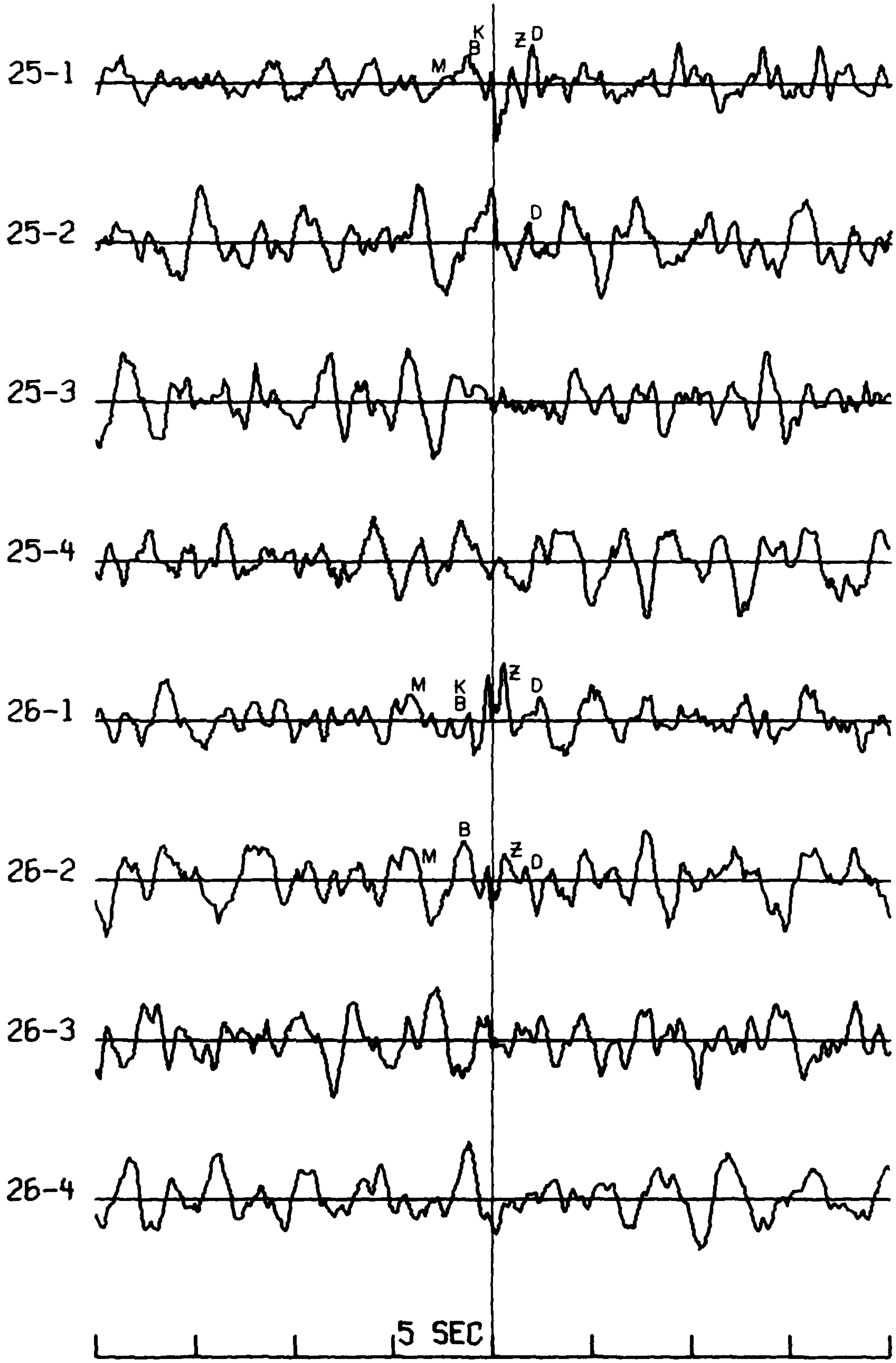
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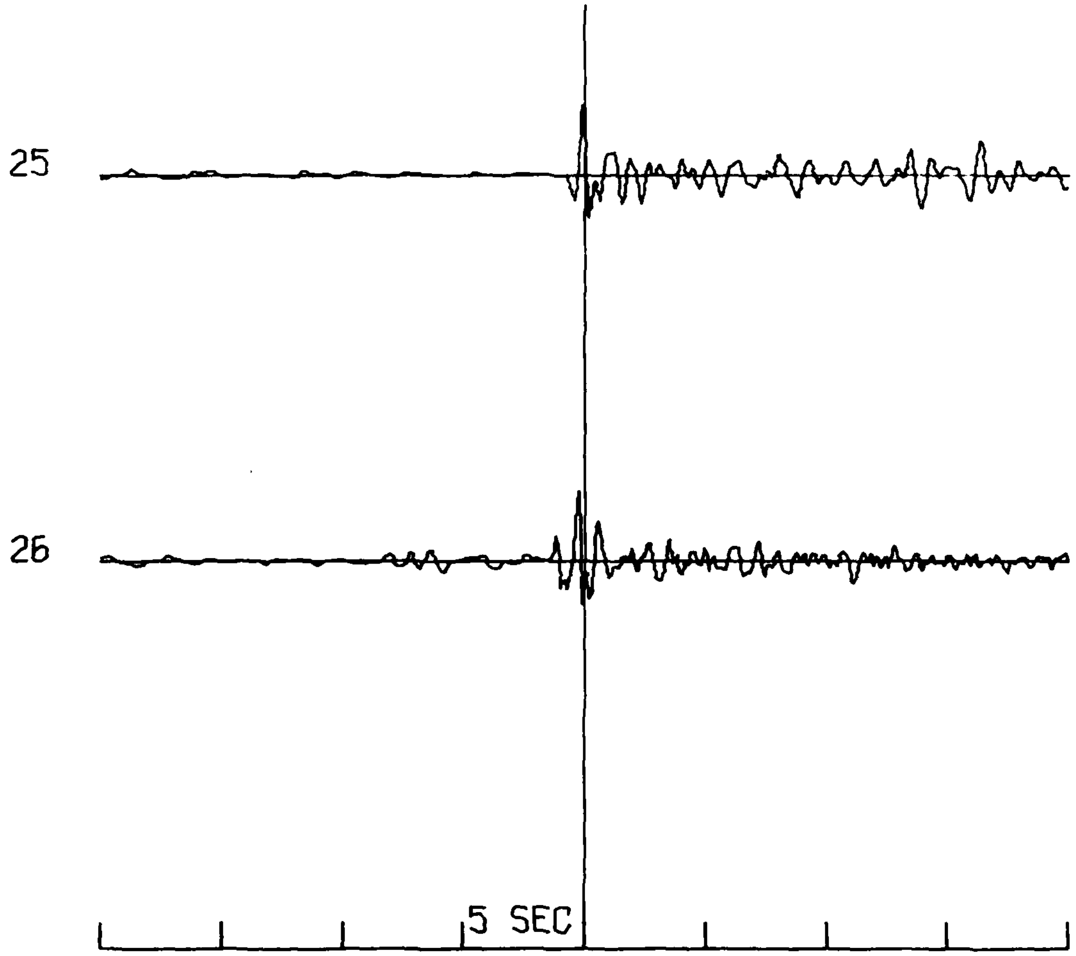
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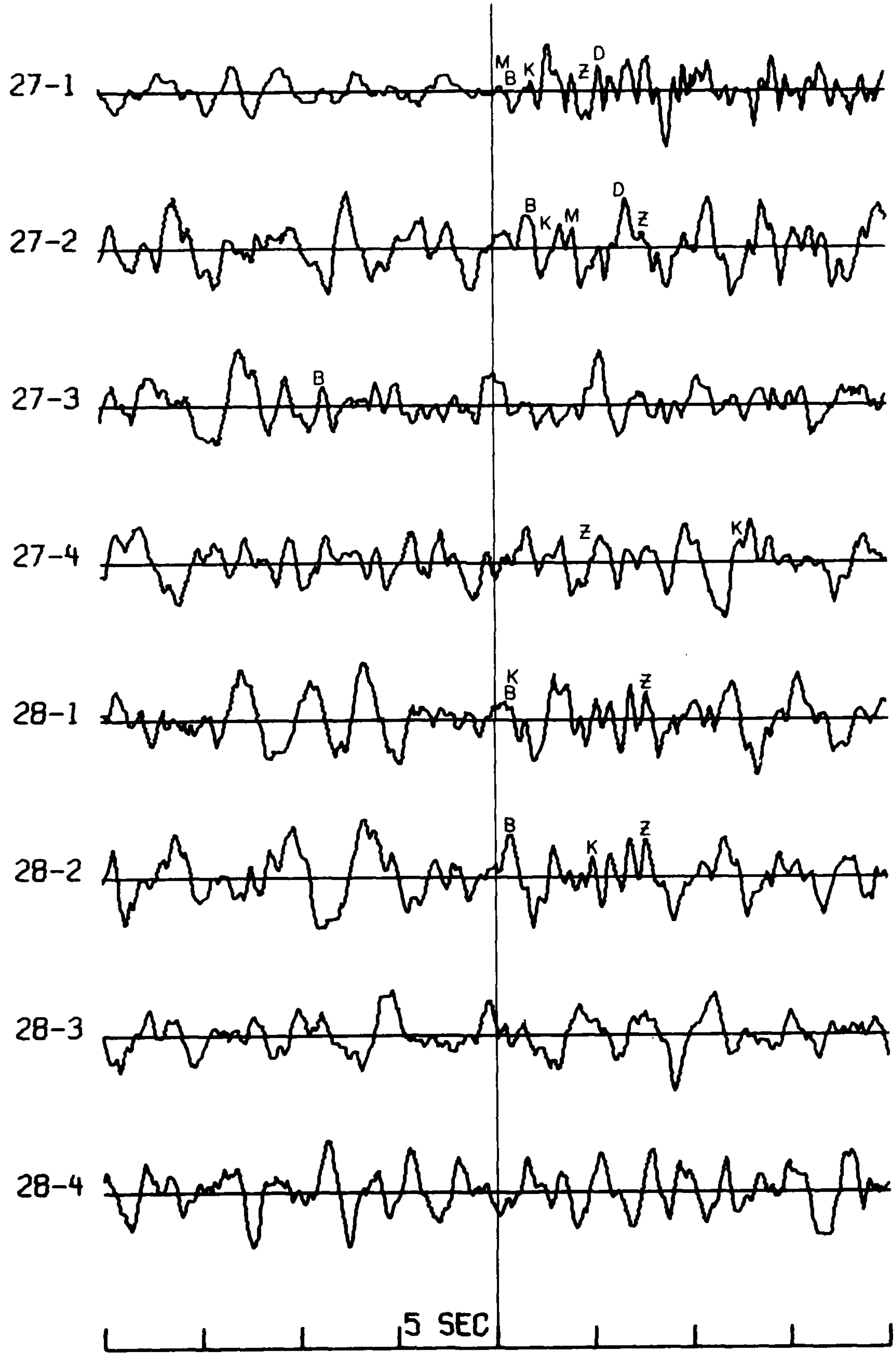
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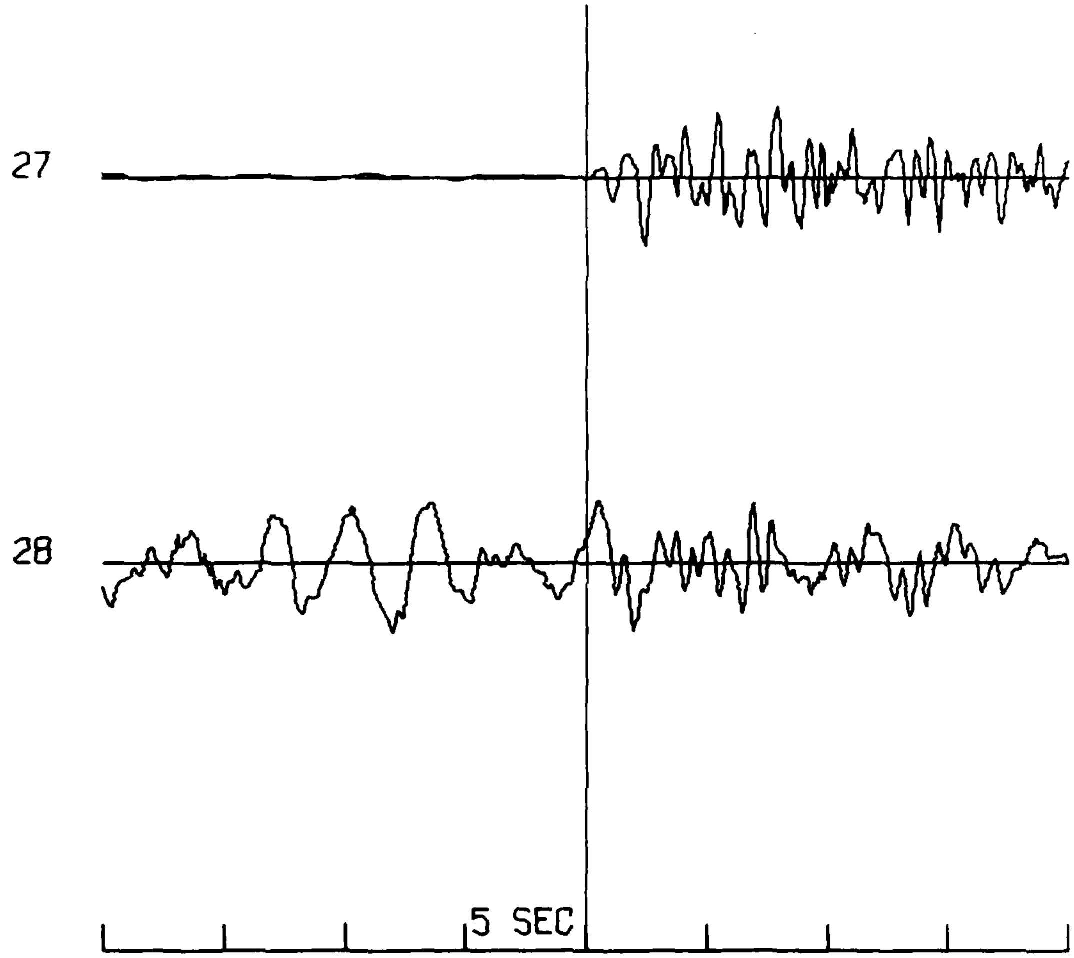
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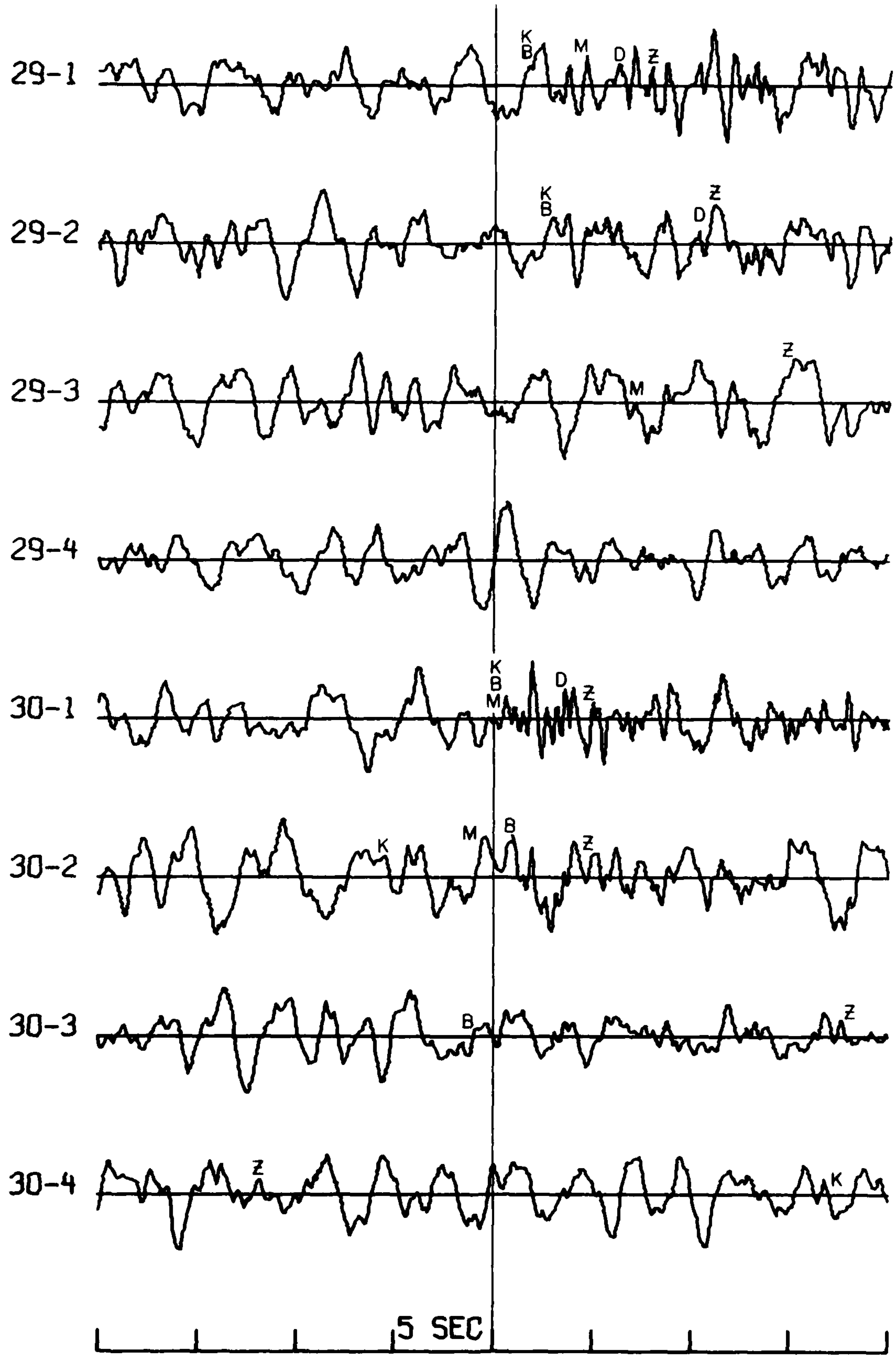
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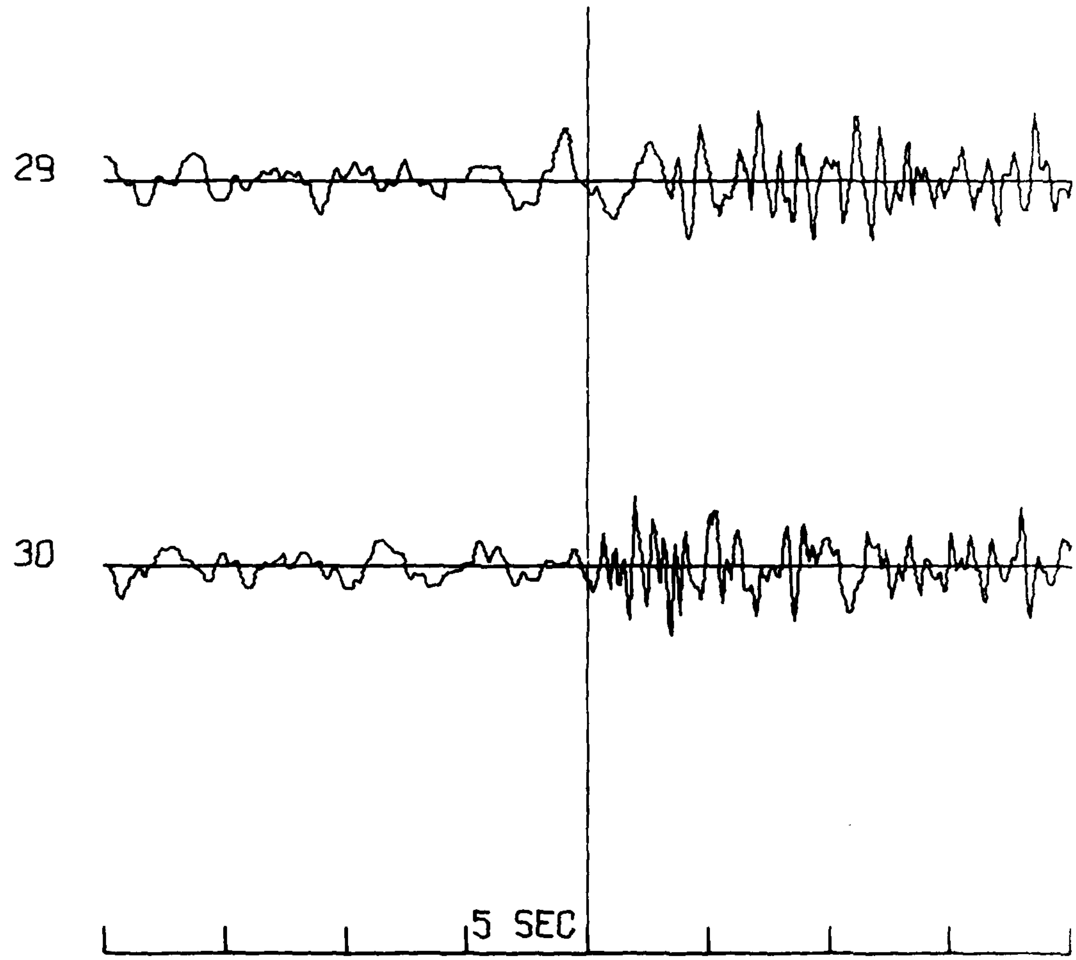
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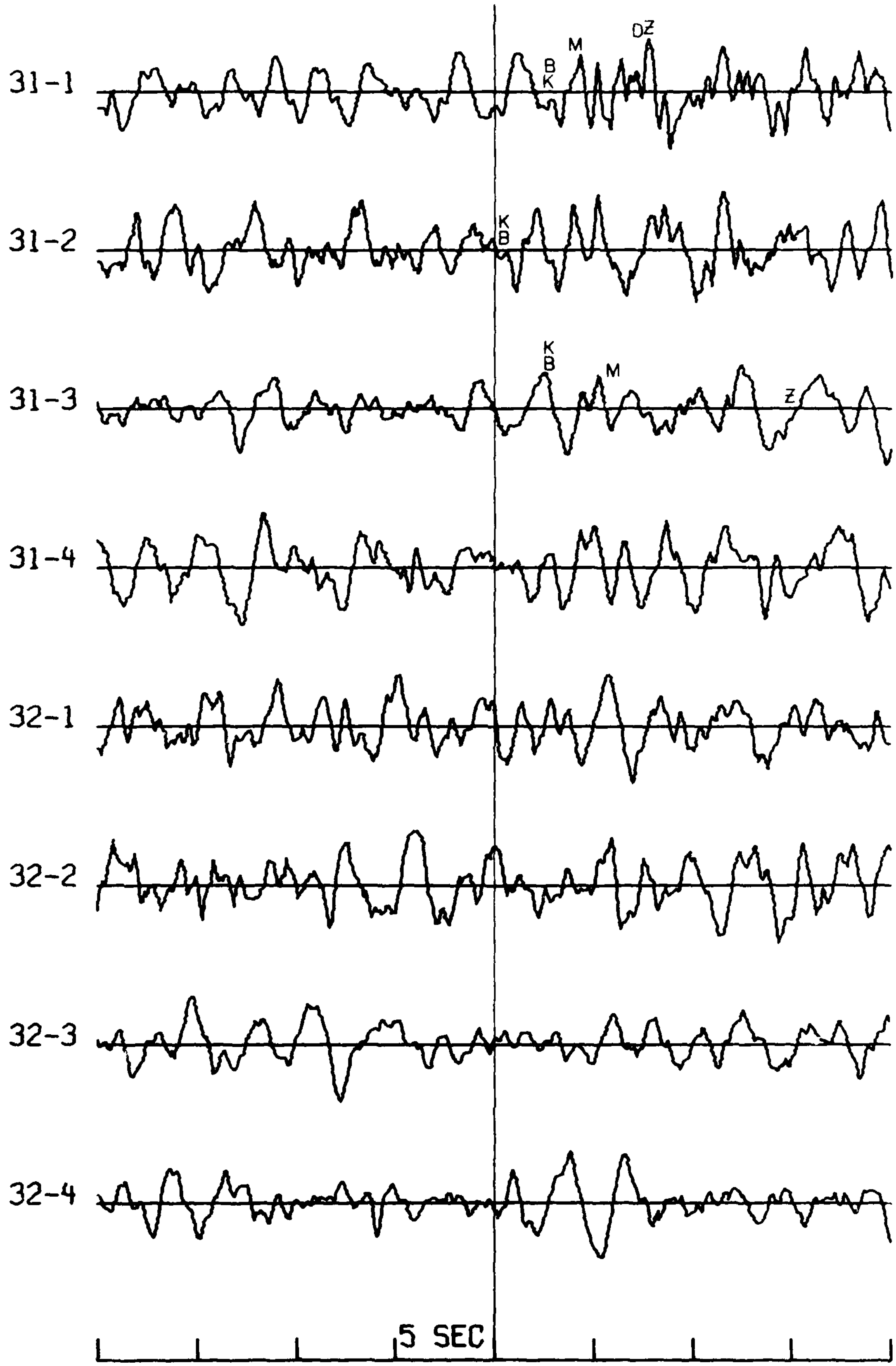
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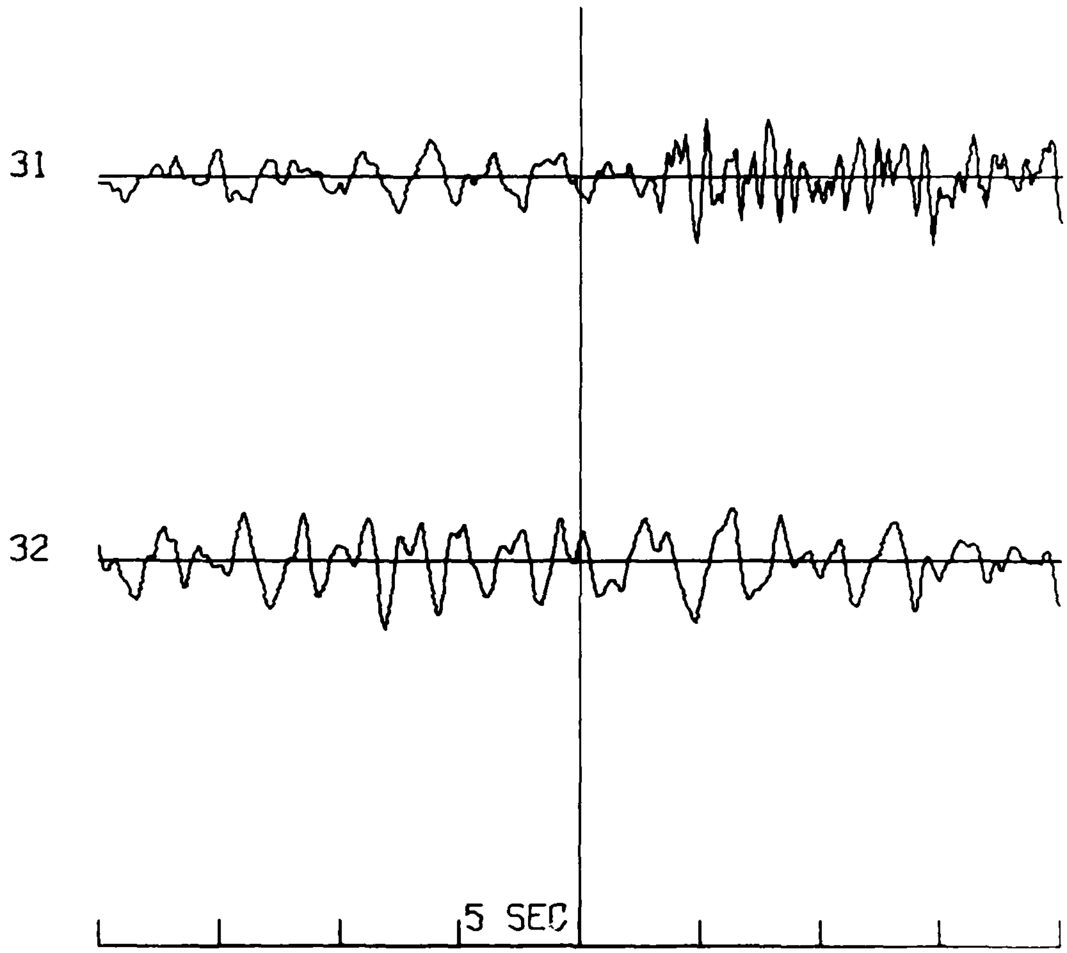
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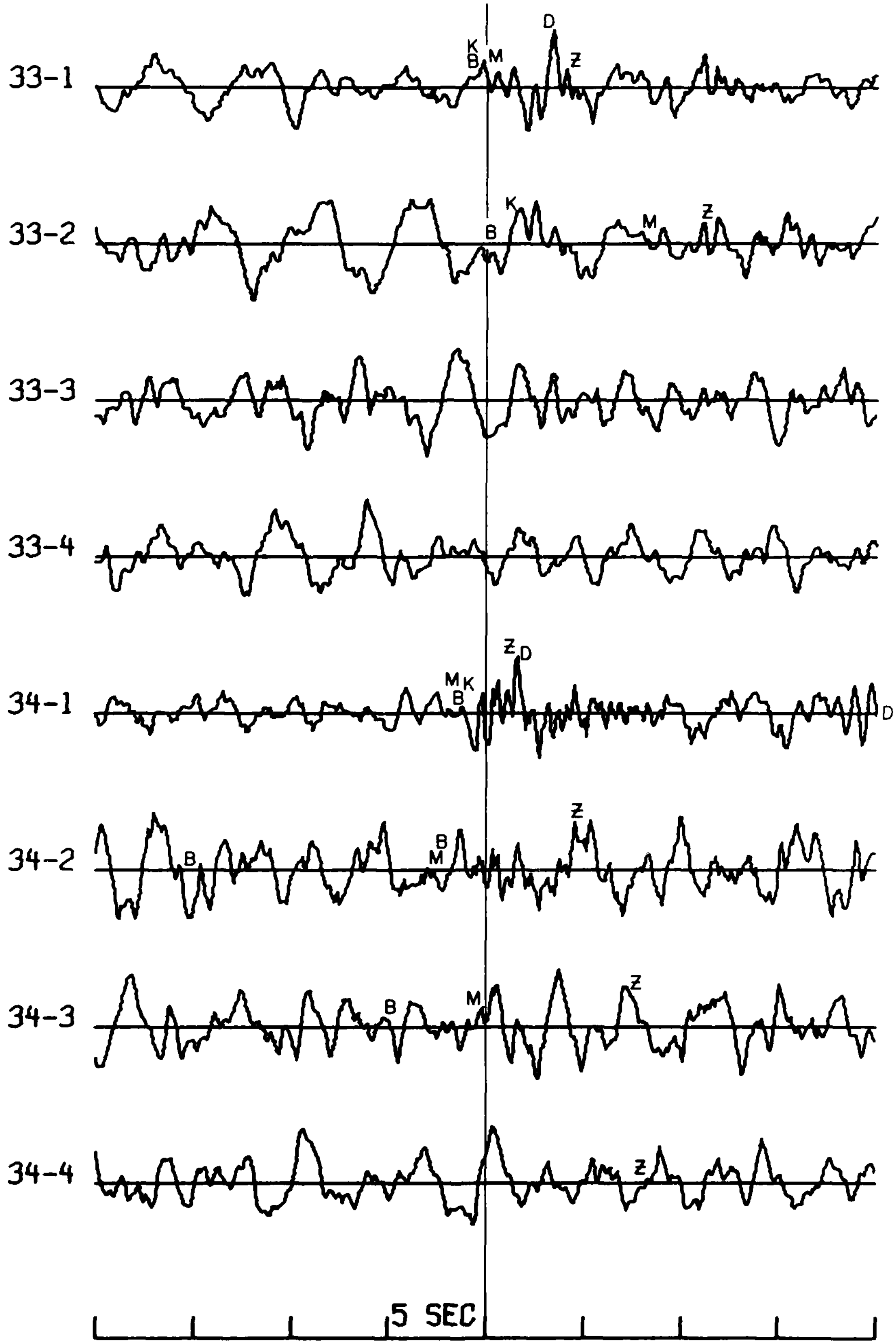
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K
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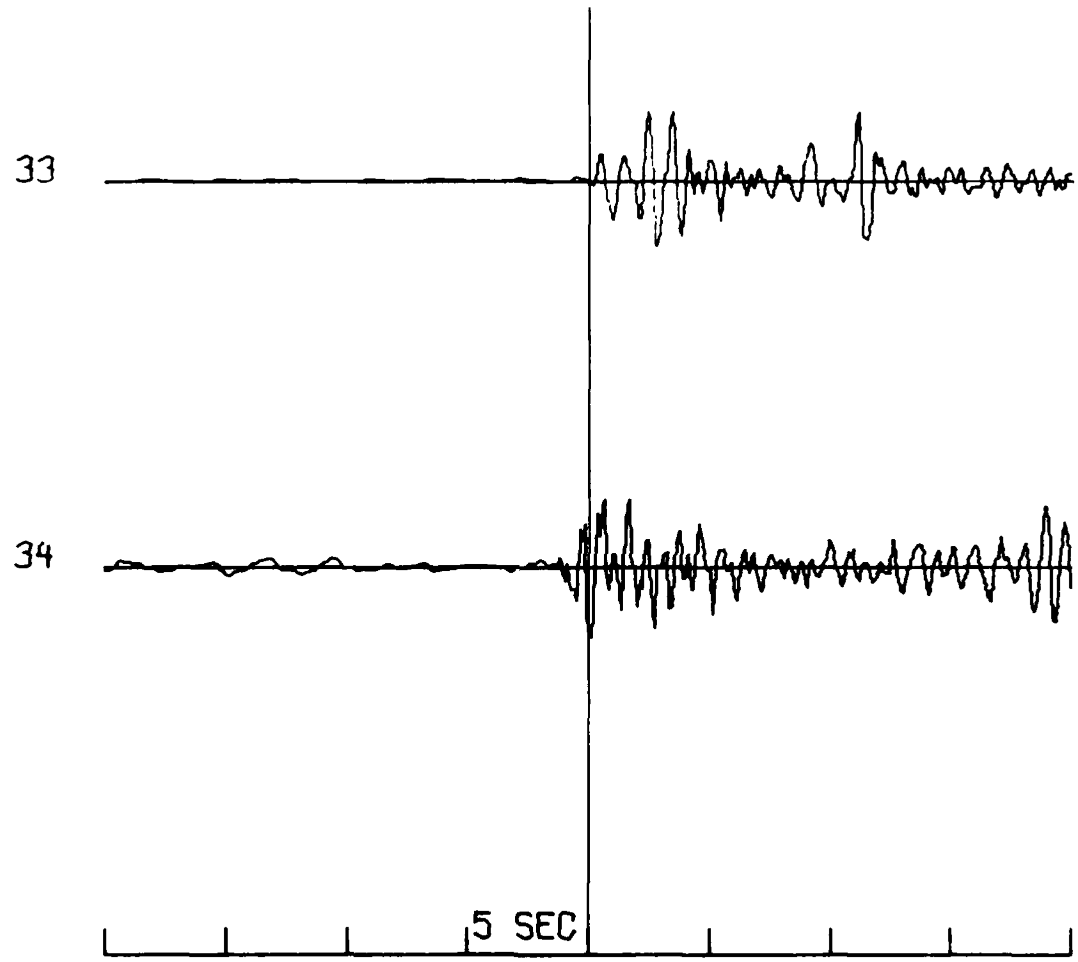
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5 SEC